Coated Conductor Development

Dean Peterson:
"Introduction and Technology Integration"

V. Selvamanickam:
"Coated Conductor Progress at IGC-SuperPower"

Paul Arendt:
"IBAD MgO Templates for YBCO Coated Conductors"

Steve Foltyn
"High Current Coated Conductors based on IBAD YSZ and Thick YBCO/Sm123 Multilayers"

FY01 Funding: $2040K (LANL)

Introduction to Coated Conductor Development

Systems Session: Vlad Matias (LANL)/Fred List (ORNL):
"Accelerated Coated Conductor Initiative: Progress Report"

- Research Parks ->New Personnel&Equipment
- Enhanced Opportunities for Partnerships

Wire Session: Maley, Holesinger, Kung, Mueller (LANL)
"Coated Conductor Research"

- Integrated TEM, scanning X-Ray Diffraction, and magnetic imaging to identify sources of current degradation.
- Research now focused on YBCO deposited on IBAD MgO

Technology Integration

- **Industrial Partners**
  - **IGC SuperPower:** Licensed IBAD Technology
  - **3M Corporation:** Committed to IBAD Development
  - **American Superconductor:** Exploring IBAD Approach
- **University Partners**
  - **Stanford**:Bob Hammond Consultant
  - **Caltech:** RHEED Texture Sensor Research (3M)
  - **Michigan/Princeton**: IBAD Modeling (3M)
- **National Labs:** Sample Exchange; Research Collaborations
  - **ORNL, ANL, BNL, NREL**

IBAD capability at 3M is driven by LANL research.

- **Materials science of MgO ion beam assisted deposition and appropriate buffers are being developed at LANL.**
- **Caltech is developing, with help from DARPA and 3M, a real time RHEED-based texture sensor which will be useful for IBAD process development.**
- **3M has a large deposition system with sputter and electron beam sources for roll-to-roll scale-up of the IBAD process.**

Although 3M has scaled RABiTS™ to longer lengths, 3M feels that IBAD may offer numerous advantages.

Scale-up of Coated Conductor Technology at IGC-SuperPower

Venkat Selvamanickam

Y. Li, C. Park, S. Sathiarju, J. Reeves, Y. Qiao, K. Lenseth, K. Zdun, G. Carota, L. Hope, M. Jones, T. Morris, J. Matshuta

IGC SuperPower

A Subsidiary of Intermagnetics General Corporation

Three-Year CRADA to Scale-up Coated Conductor Technology

- CRADA executed among IGC, LANL, and ANL in January 2000 to scale-up Coated Conductor process to full-fledged manufacturing.
- CRADA was an outcome of an excellent match between manufacturing requirements and DOE Lab demonstrations.

<u>IGC Requirements</u>

High Yield, High Throughput, High Amperage, Simple Controls

<u>LANL Demonstration</u>

Simple, Proven, Reproducible, High Rate Process with Few Variables

Strong collaboration between IGC-SuperPower & LANL

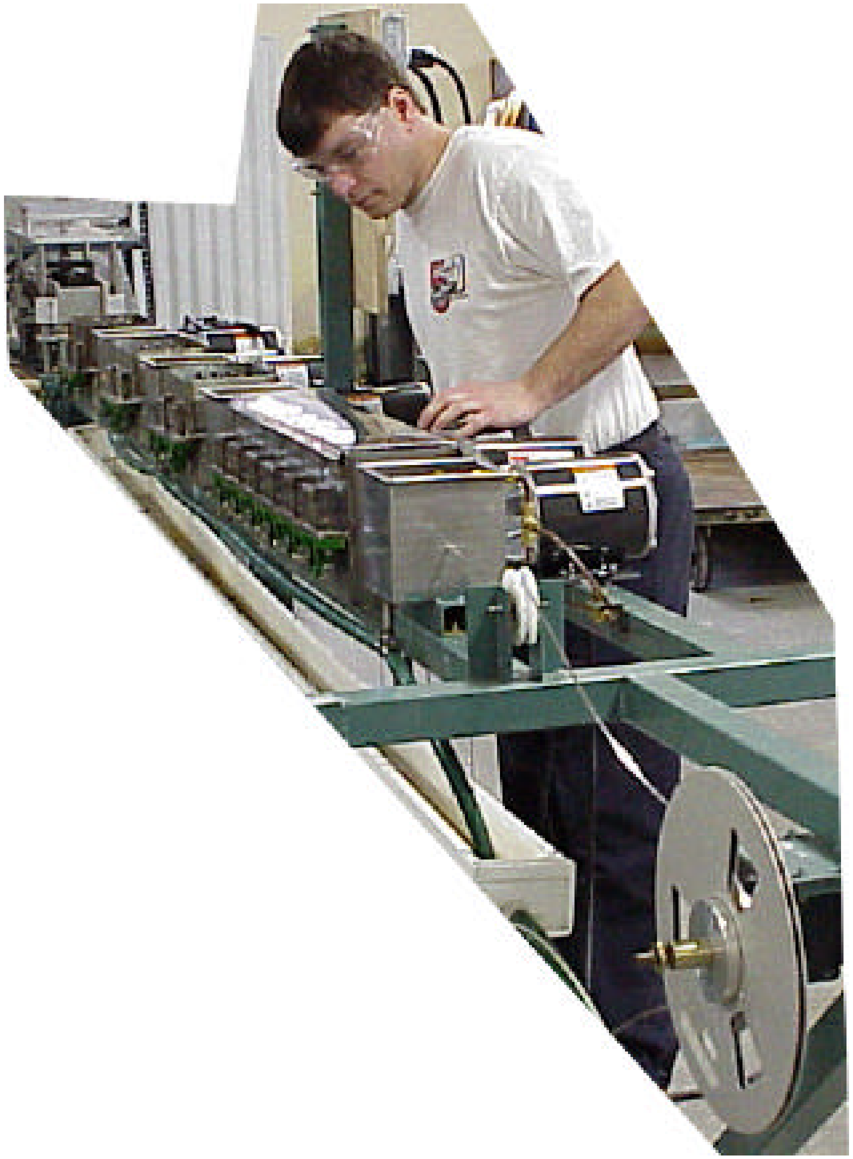
- Open and close cooperation between IGC-SuperPower and LANL in scale-up efforts.
- Quarterly meetings held regularly to evaluate progress.
- Weekly conference calls to assure good and timely feedback.
- IGC scientists and engineers training at LANL process facilities.
- LANL personnel visits to IGC-SuperPower to evaluate and assist in characterization techniques.
- Key process patents licensed to IGC-SuperPower.

IGC-SuperPower Has Invested Substantial Resources to Scale-up Coated Conductor Technology

- Pilot-scale manufacturing facilities in a 1000 sq.ft. Class-10,000 cleanroom - expanded to 2000 sq.ft. in June ‘01.
- Cleanroom houses pilot-scale buffer and YBCO deposition facilities and characterization equipment.
- Auxiliary systems, e.g. reel-to-reel polishing rig

Long Lengths of Metal Substrates Are Routinely Polished with Reel-to-Reel Polishing Rig

- Reel to reel polishing rig designed and constructed to polish > 100 m lengths of metal substrate for coated conductor with a high degree of surface smoothness, in 1 pass.
- Several tens of meters of metal tapes have been polished for buffer deposition



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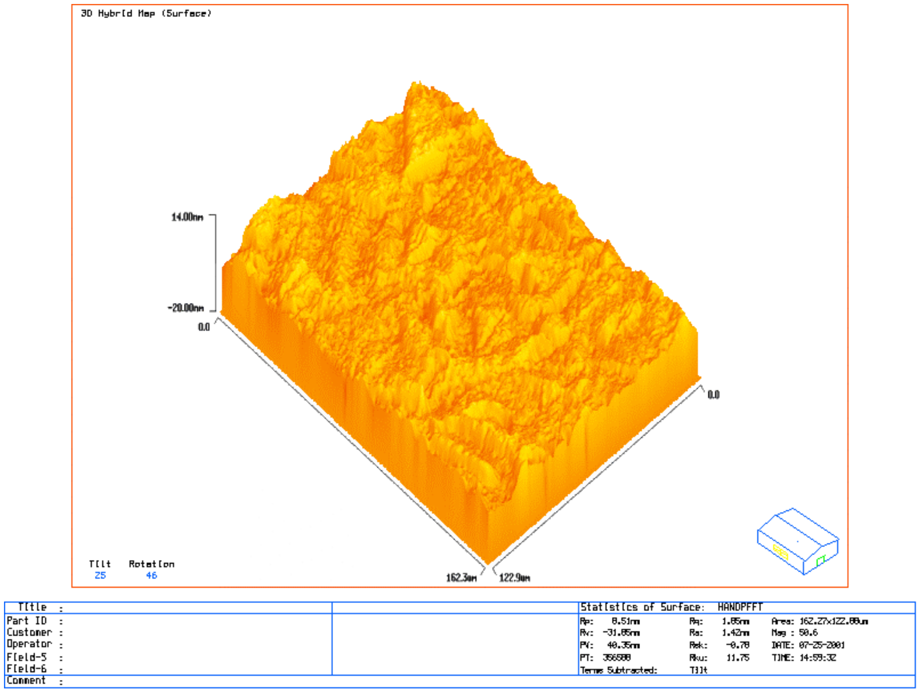
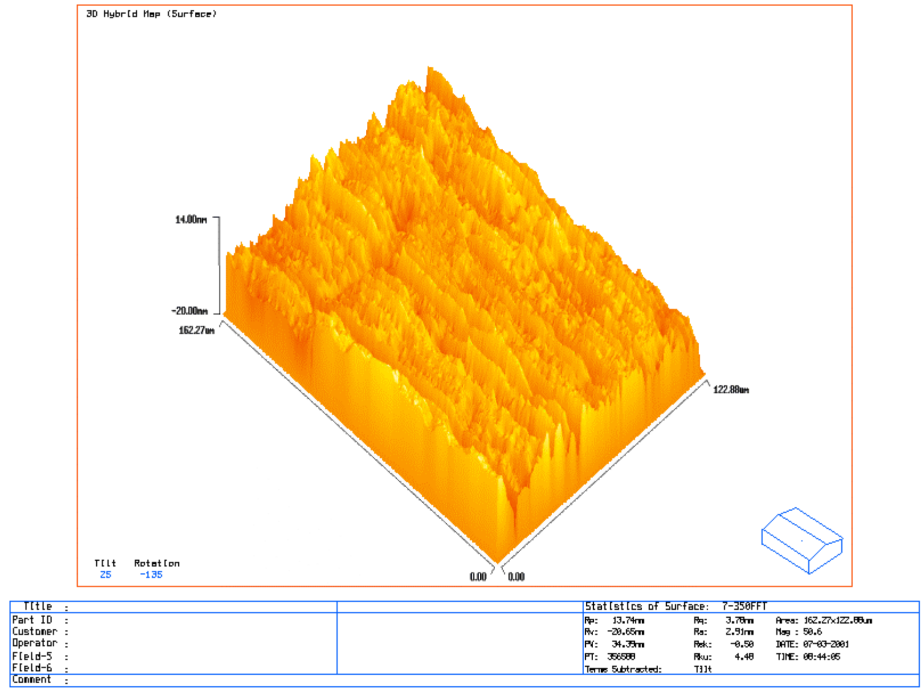
Surface Roughness of tapes polished continuously comparable with manually-polished tapes



Manually Polished

Ra = 1.5 nm over 20,000 micron^2 area



Continuously Polished

Ra = 2.9 nm over 20,000 micron^2 area

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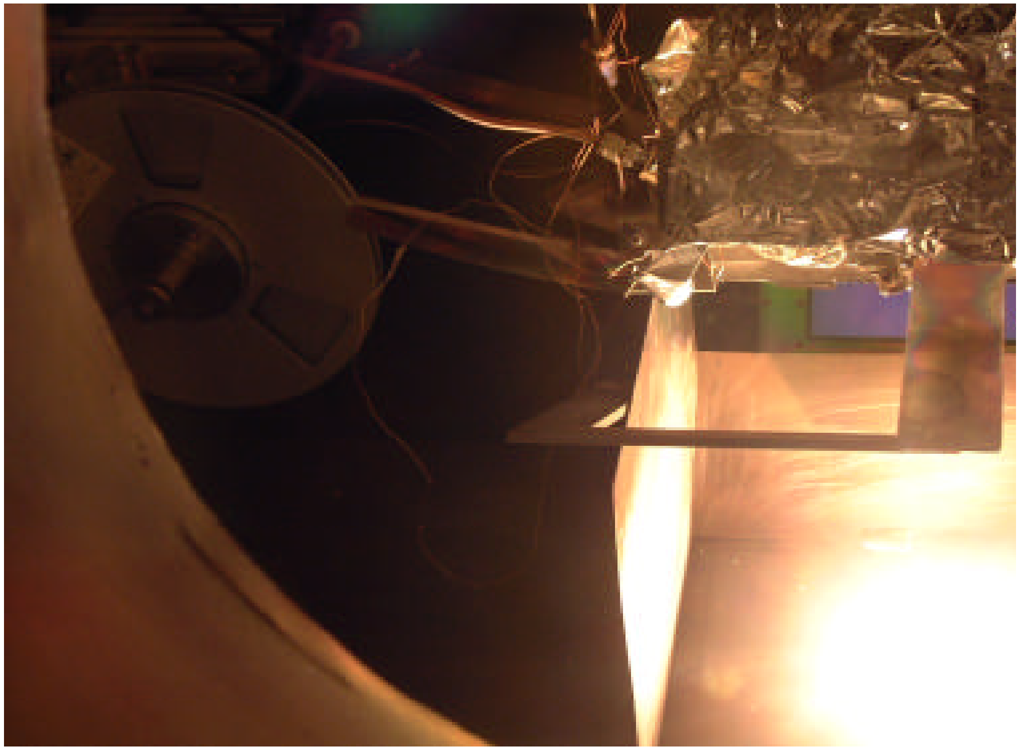
Pilot-scale Buffer Deposition Facility Established at IGC-SuperPower in Dec. 2000

Pilot-scale Buffer Deposition Facility is designed for long, continuous operations



- 56” cube Box Coater
- Equipment rated for continuous operation > 600 hours; > 20 cm deposition zone
- Continuous source feed with >1 week supply.

SuperPower LLC
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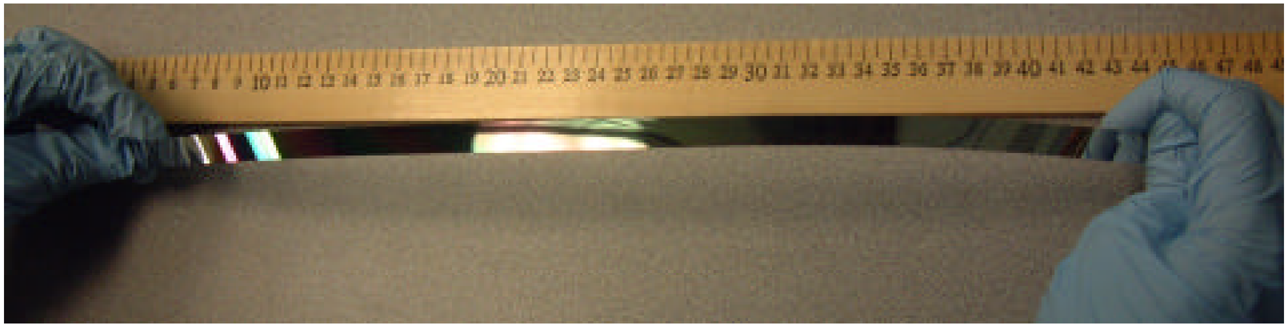
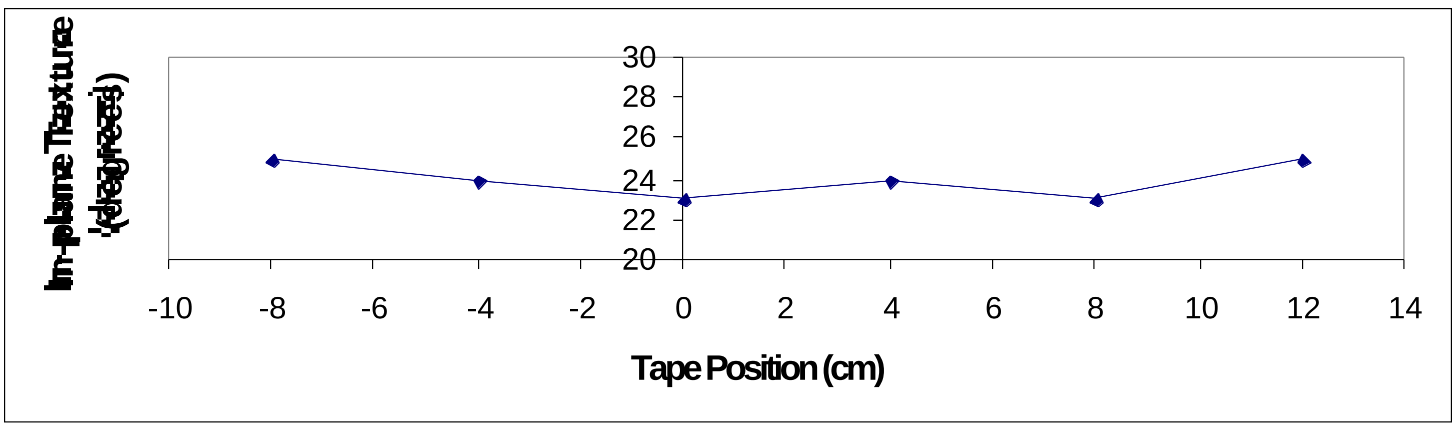
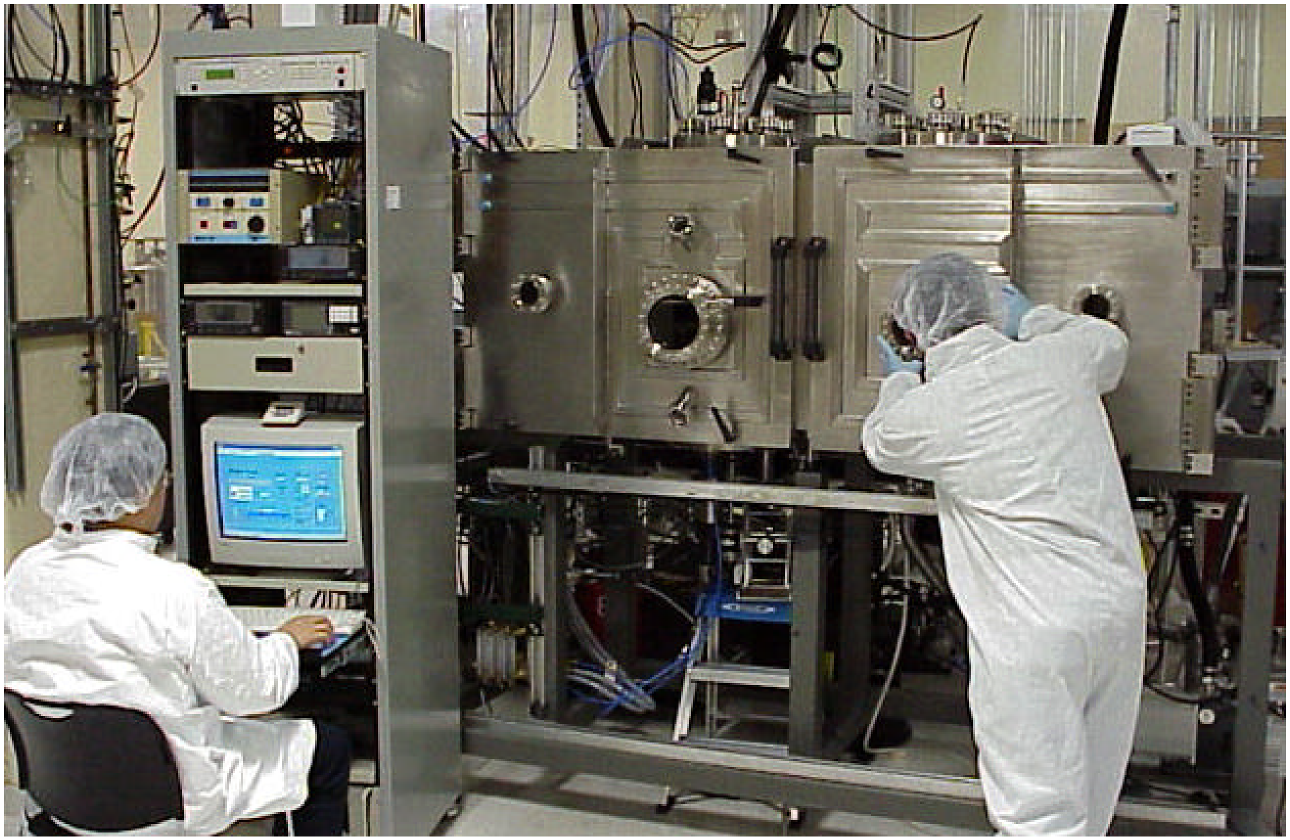
Uniform Buffer Layer Deposition in Pilot-Scale Facility



20-cm-long tapes with buffer layers produced with uniform texture (±1 degree)



Pilot-Scale YBCO Deposition Facility Established in Dec. 2000



- 78-in.-long vacuum chamber for YBCO and Ag sputtering
- Computer-controlled target rotation, rastering, indexing.
- Automatic monitoring and control of target erosion beam energy inside chamber

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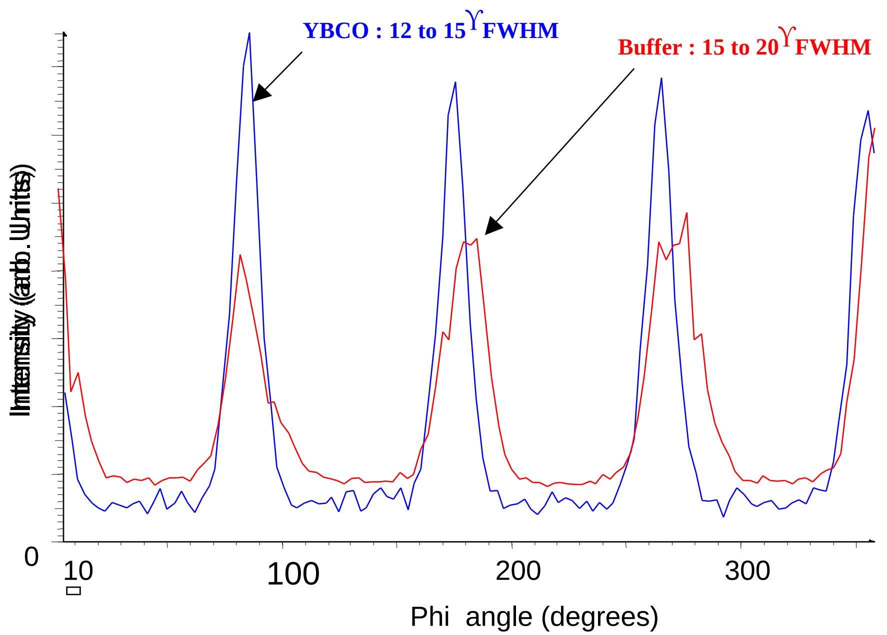
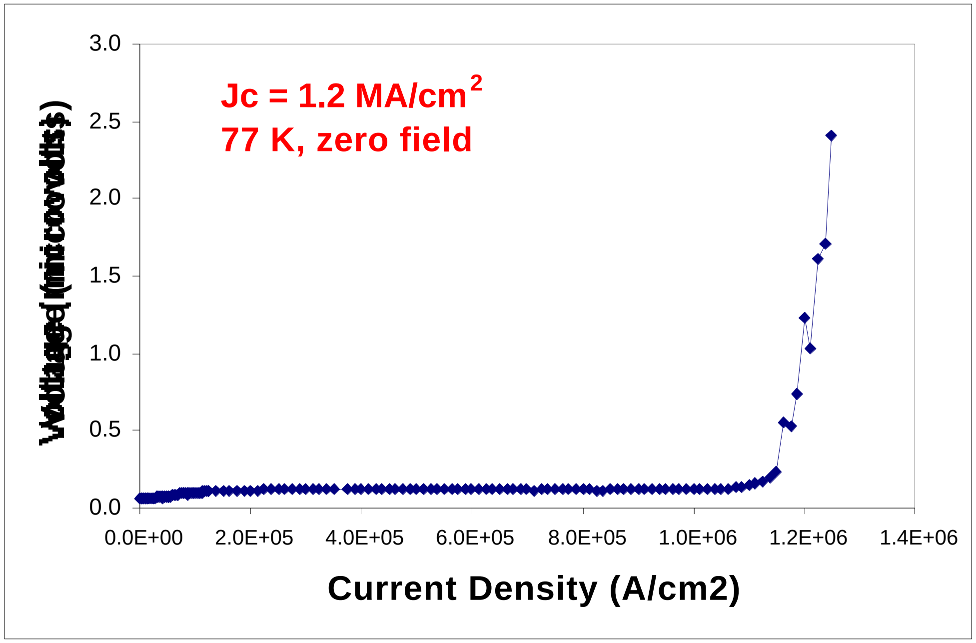
High-Quality YBCO Coatings Produced in Pilot-Scale Facility





- J_c attained on metal substrates:
  1 - 2 MA/cm^2, typical; 4 MA/cm^2, max.

IGC SuperPower LLC
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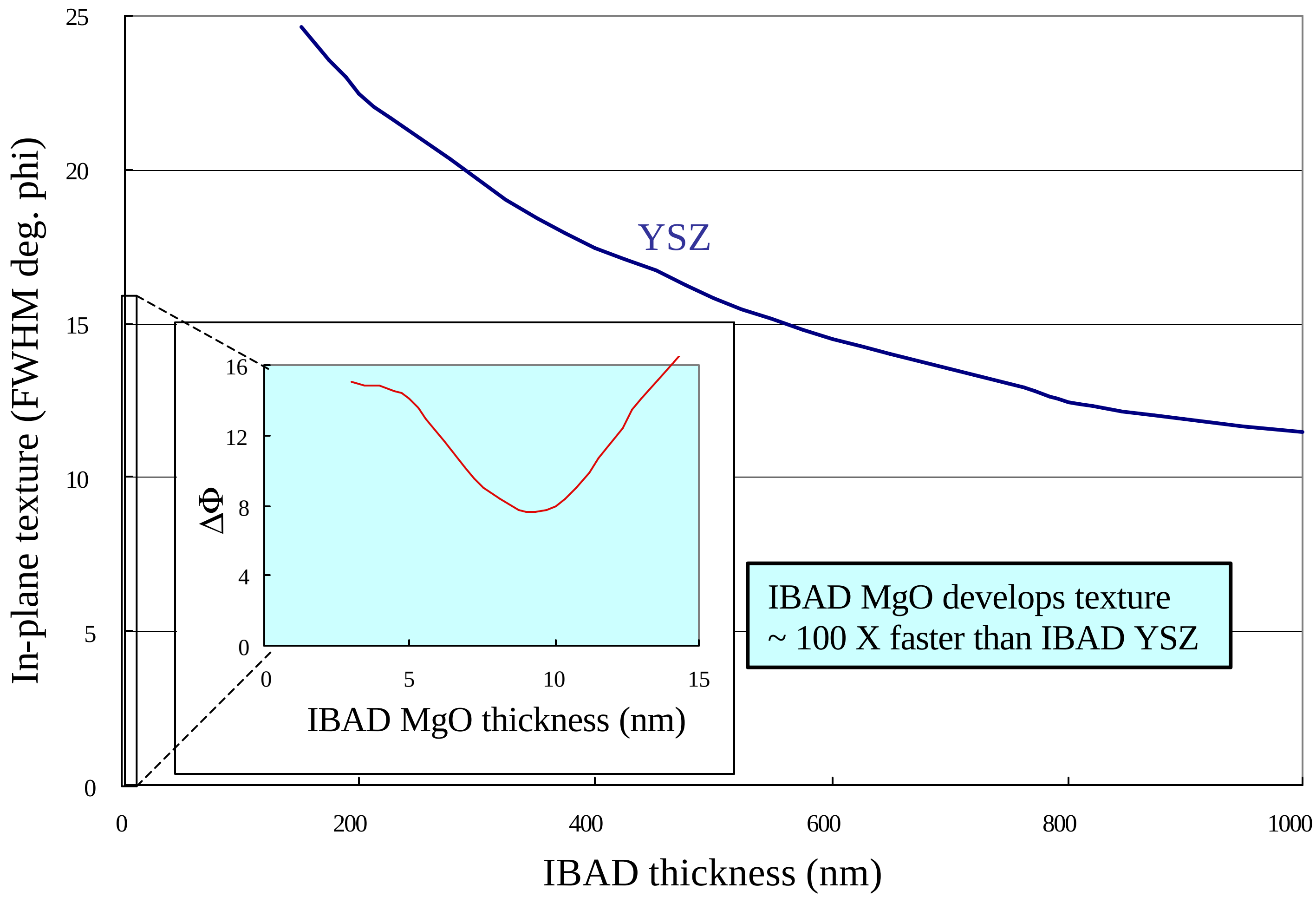
IGC-SuperPower continues to aggressively scale up Coated Conductor technology to manufacturing operations with a close collaboration with LANL.

IBAD MgO Templates for YBCO Coated Conductors

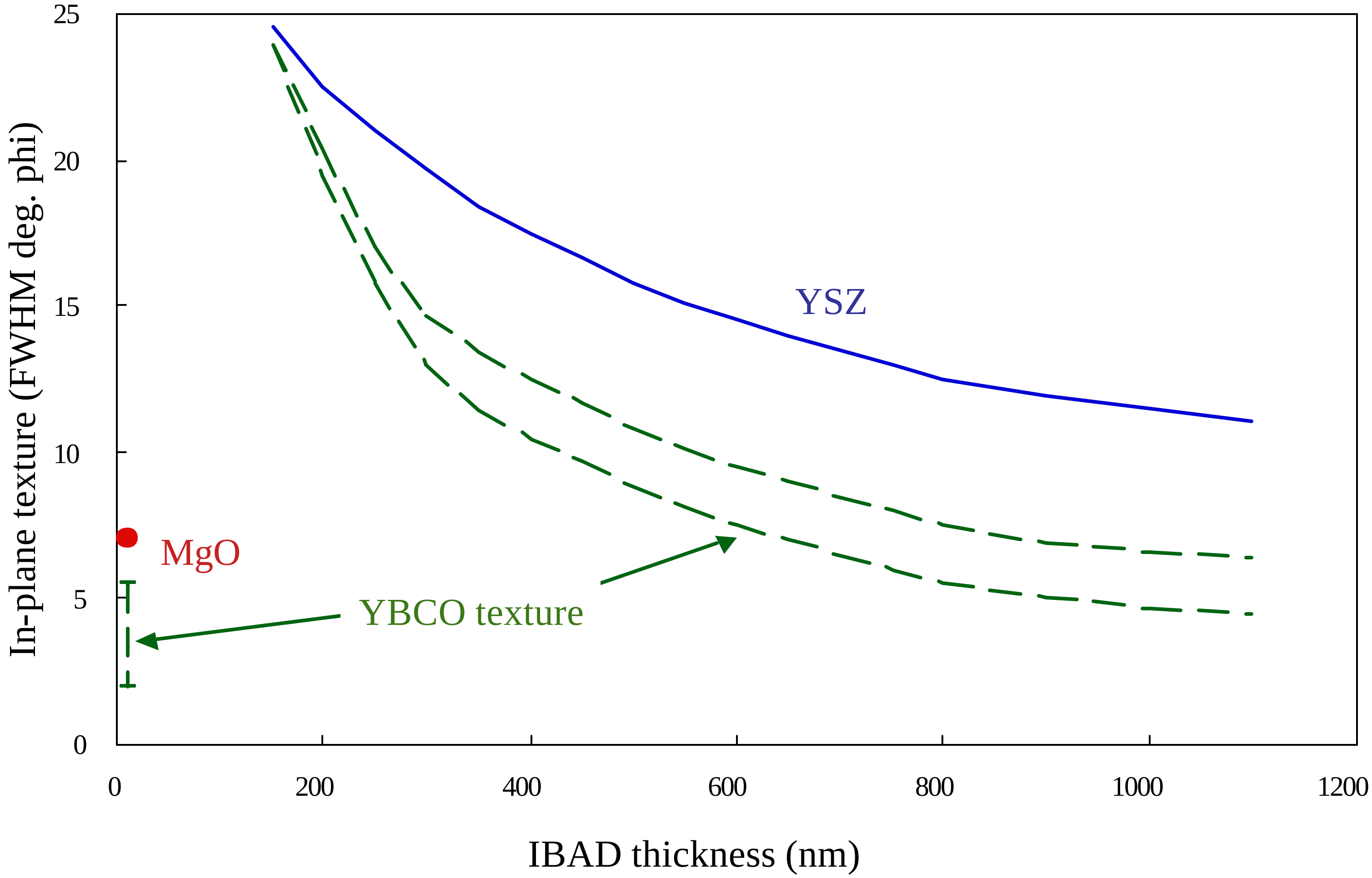
Paul Arendt, Steve Foltyn, Randy Groves, Terry Holesinger, Harriet Kung,
Quanxi Jia, Vladimir Matias, Eric Peterson, Luke Emmert, Ray DePaula,
Paul Dowden, Yates Coulter, Liliana Stan

Superconductivity Technology Center
Materials Science and Technology Division
Los Alamos National Laboratory

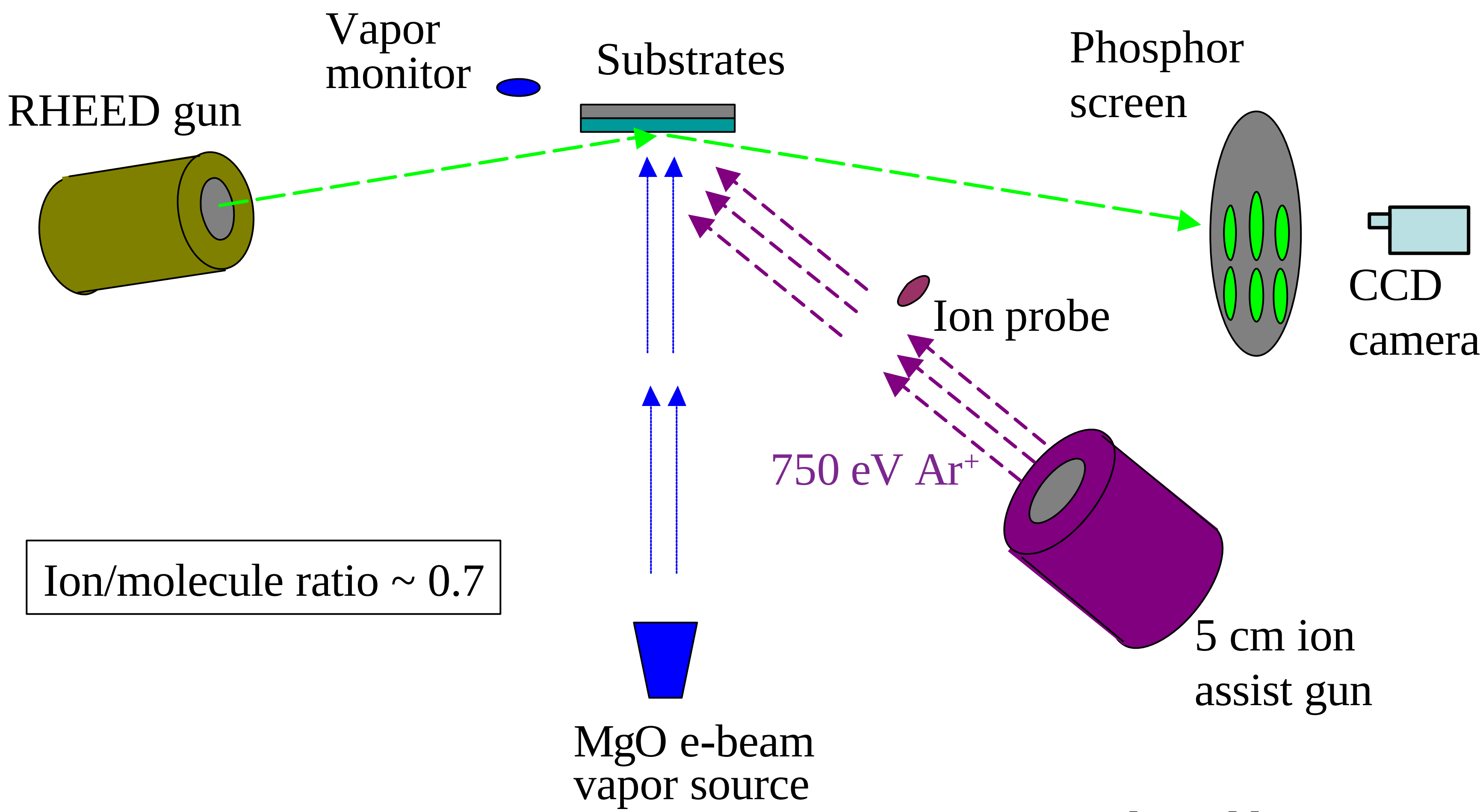
Why use IBAD MgO?



In-plane texture improvement is observed for YBCO films deposited on IBAD templates

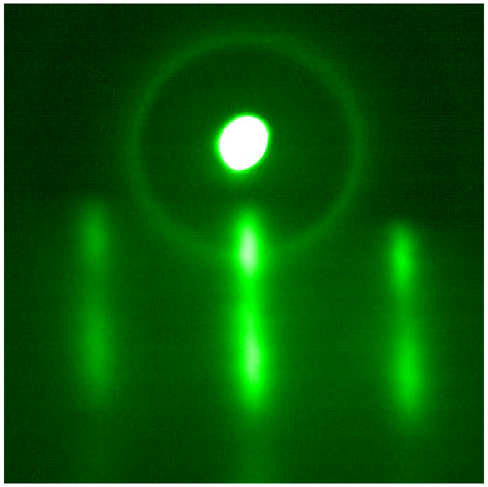


MgO research chamber schematic



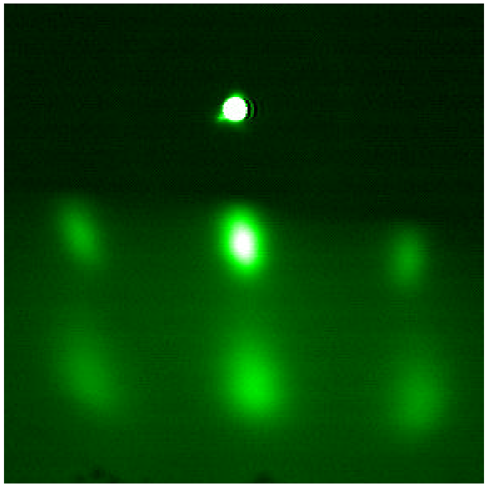
IBAD MgO film growth can be monitored for "quality" during deposition

homoepi MgO/SXAL MgO



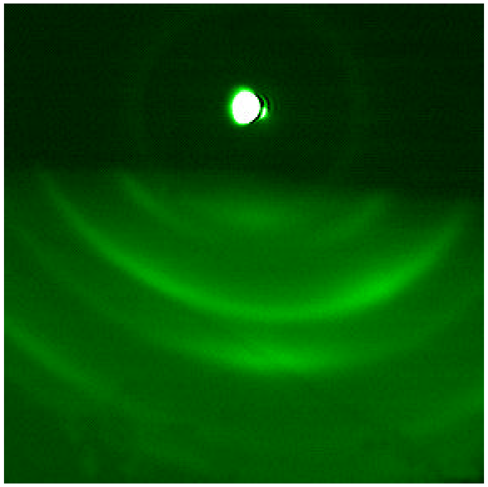
Rod-like

IBAD MgO/a-Si_3N_4/Si



Spot-like

e-beam evaporated MgO without ion assist



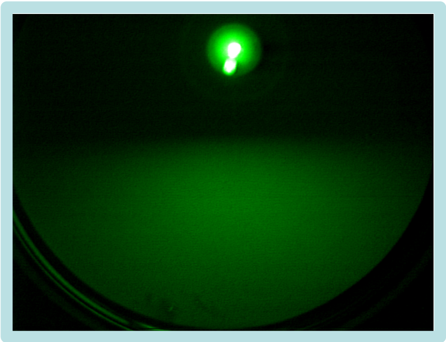
Ring-like

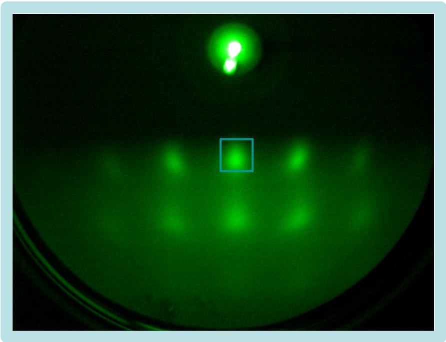
Spot intensity vs. time can be used to monitor growth of IBAD

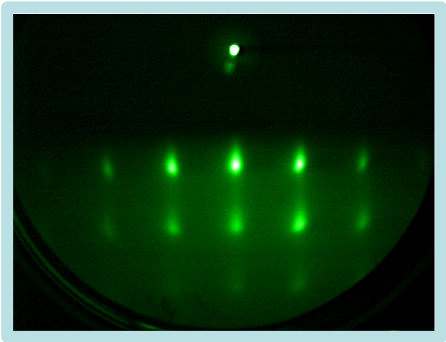
QuickTime™ and a
BMP decompressor
are needed to see this picture.

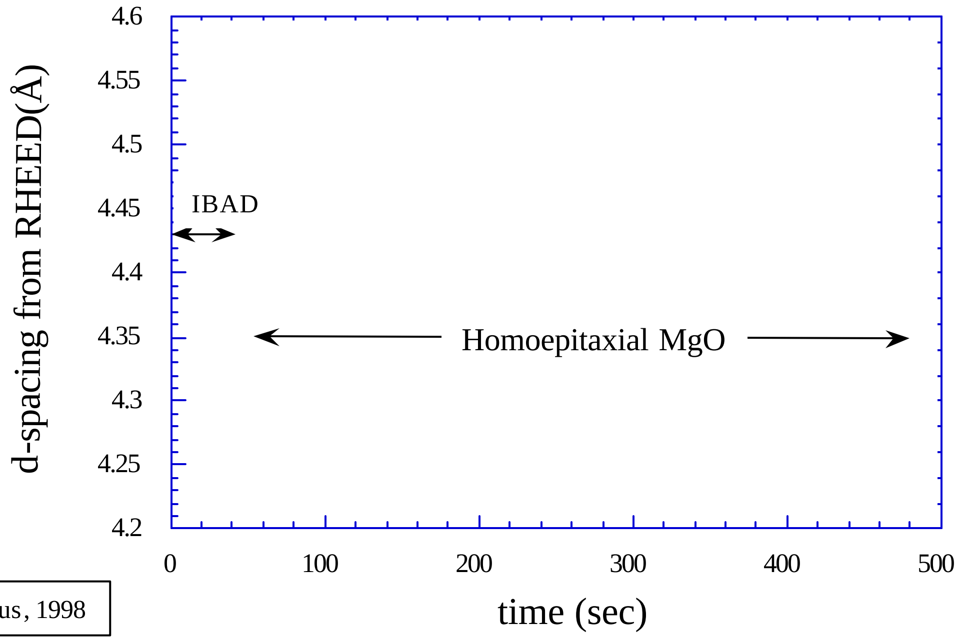
RHEED pattern evolution during growth of MgO*

a-Si_3N_4 substrate | **after IBAD MgO** | **after homoepi MgO**



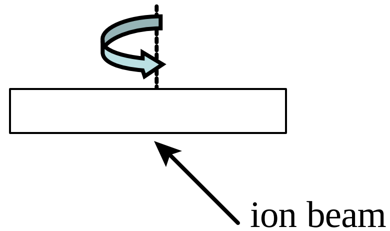




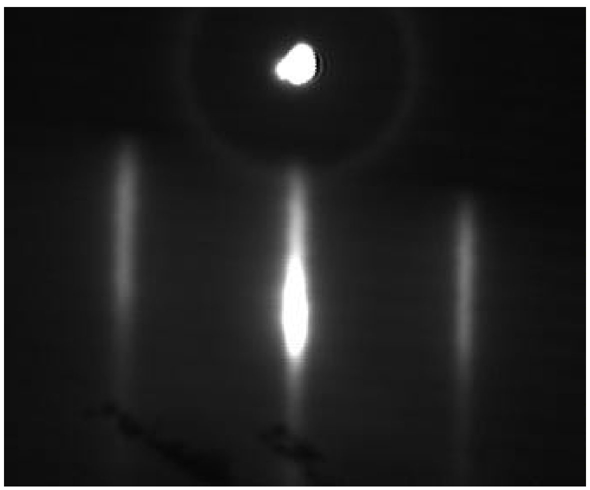


*V. Matijasevic, Conductus, 1998

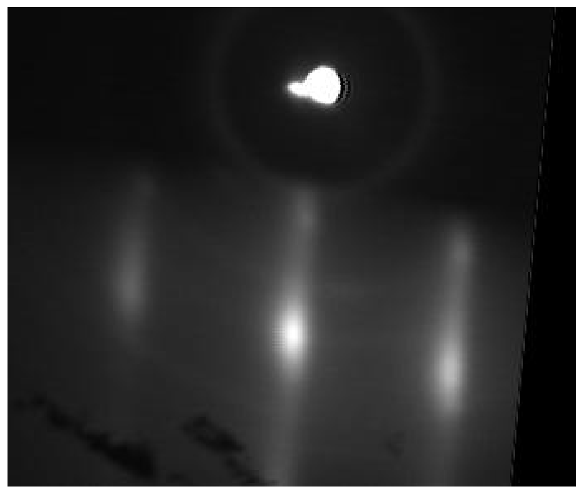
Observed tilting of spot patterns when sample was rotated 90° with respect to direction of ion assist beam



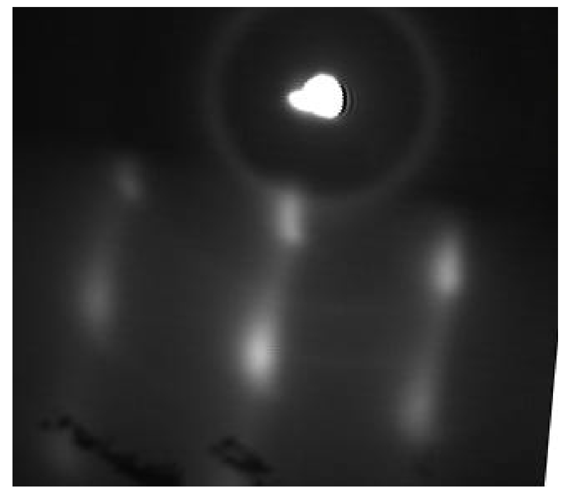
100 Å



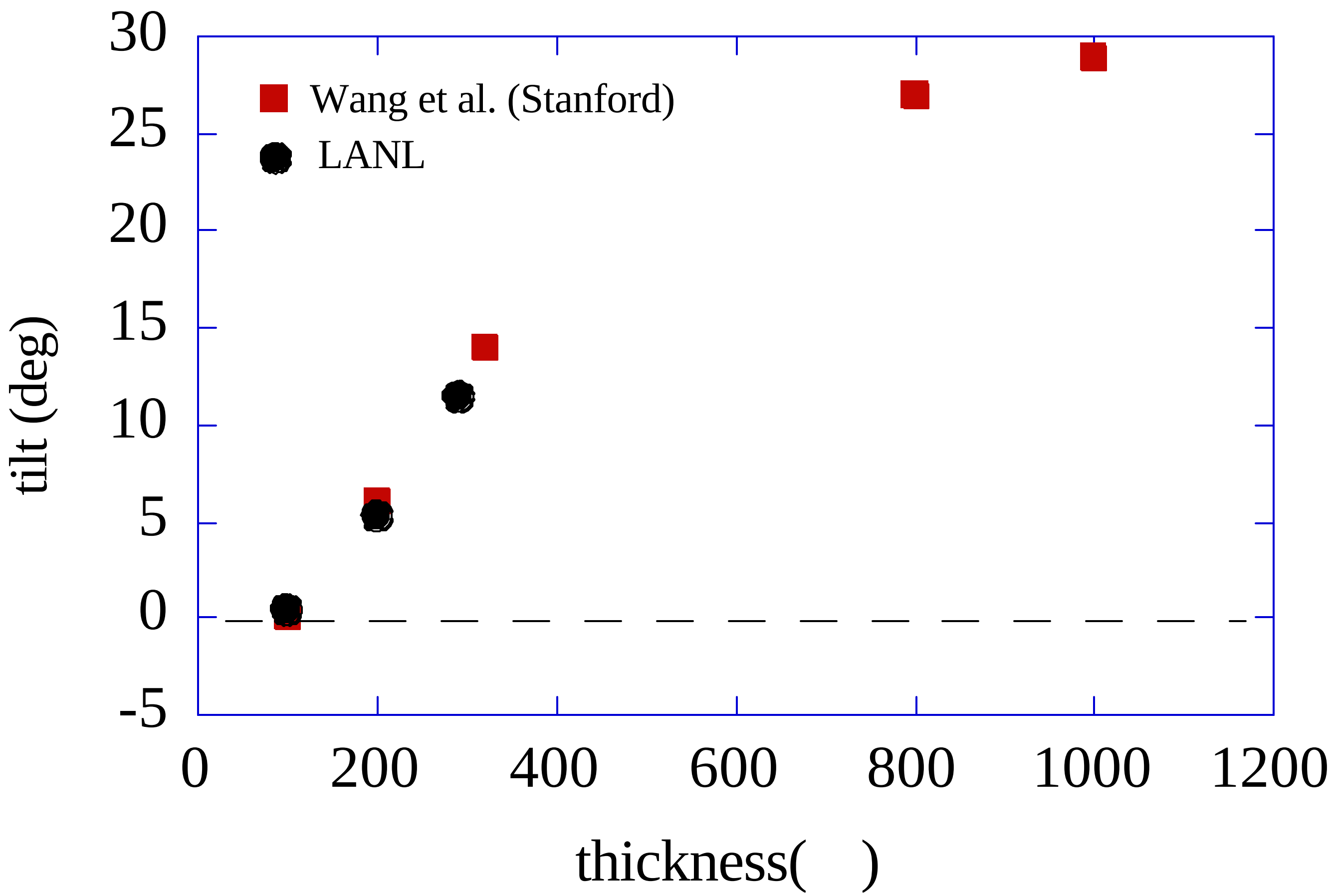
200 Å



300 Å

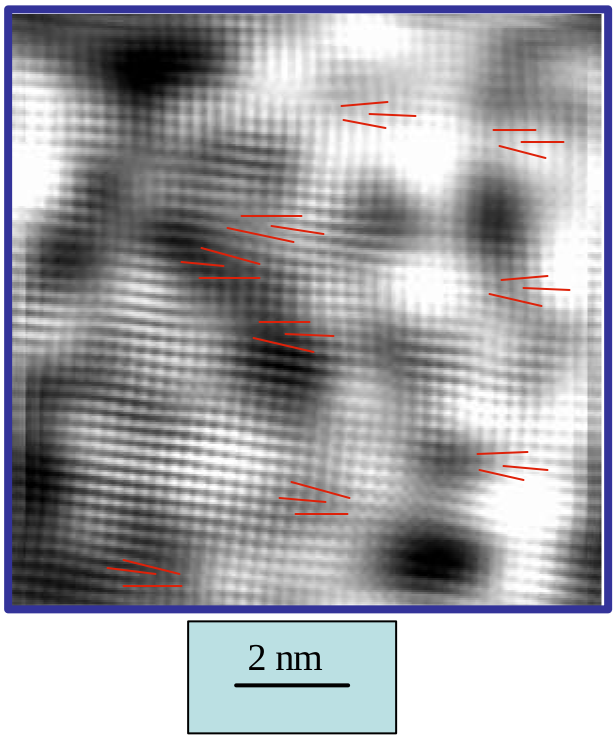


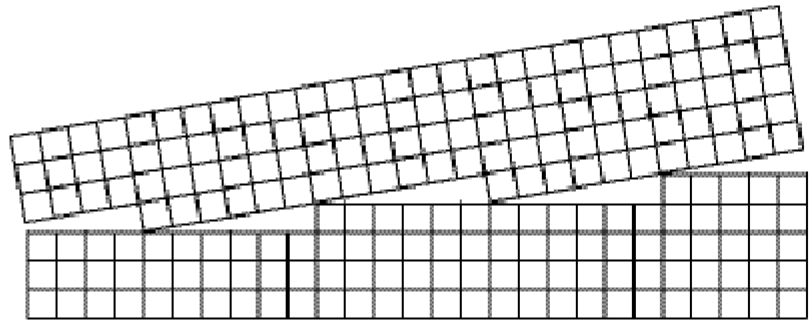
Lattice tilting continues with increasing IBAD thickness

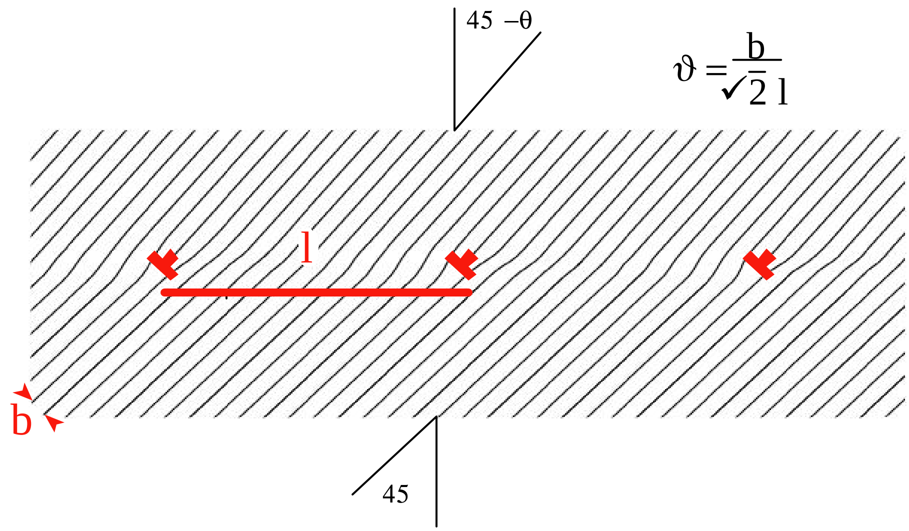


Radiation-induced dislocations in IBAD MgO provide a mechanism for lattice tilting

Interstitial point defects coalesce to form {110} type planes

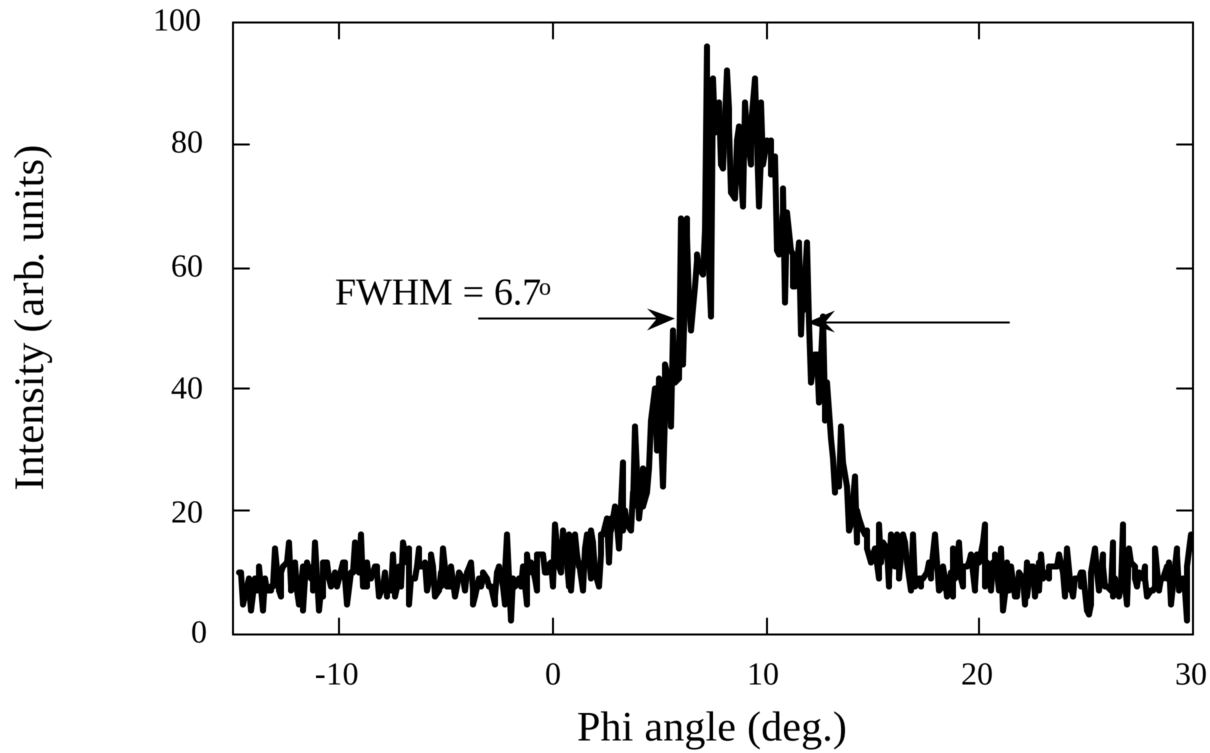






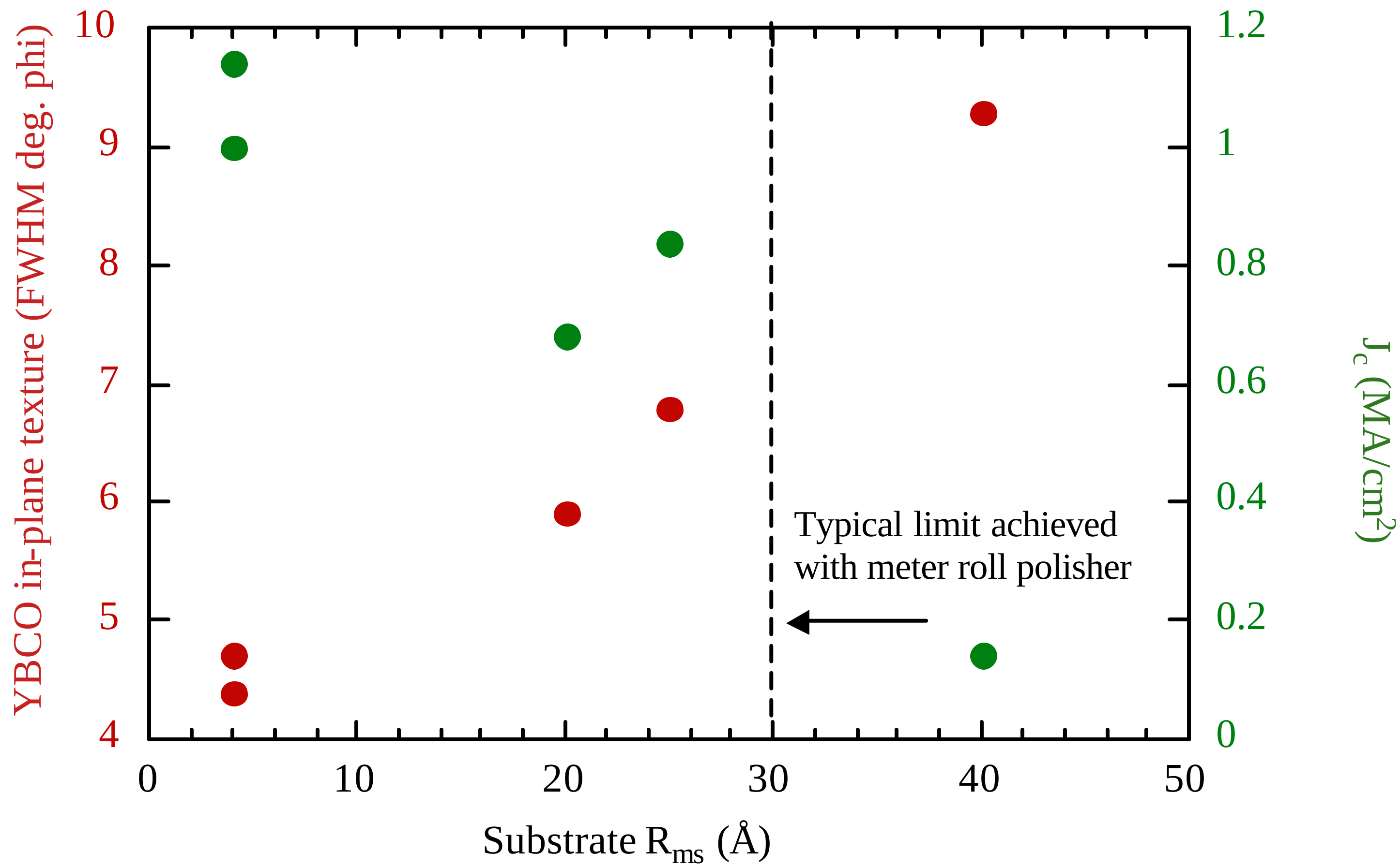
~ 10^{12} dislocations/cm^2 in 200 Å allows a 5^o tilt

Calibration of RHEED I vs. t curve with XRD results allowed for optimization of IBAD MgO in-plane texture



homoepi-MgO/IBAD MgO/ a-Si_3N_4/bp-C276

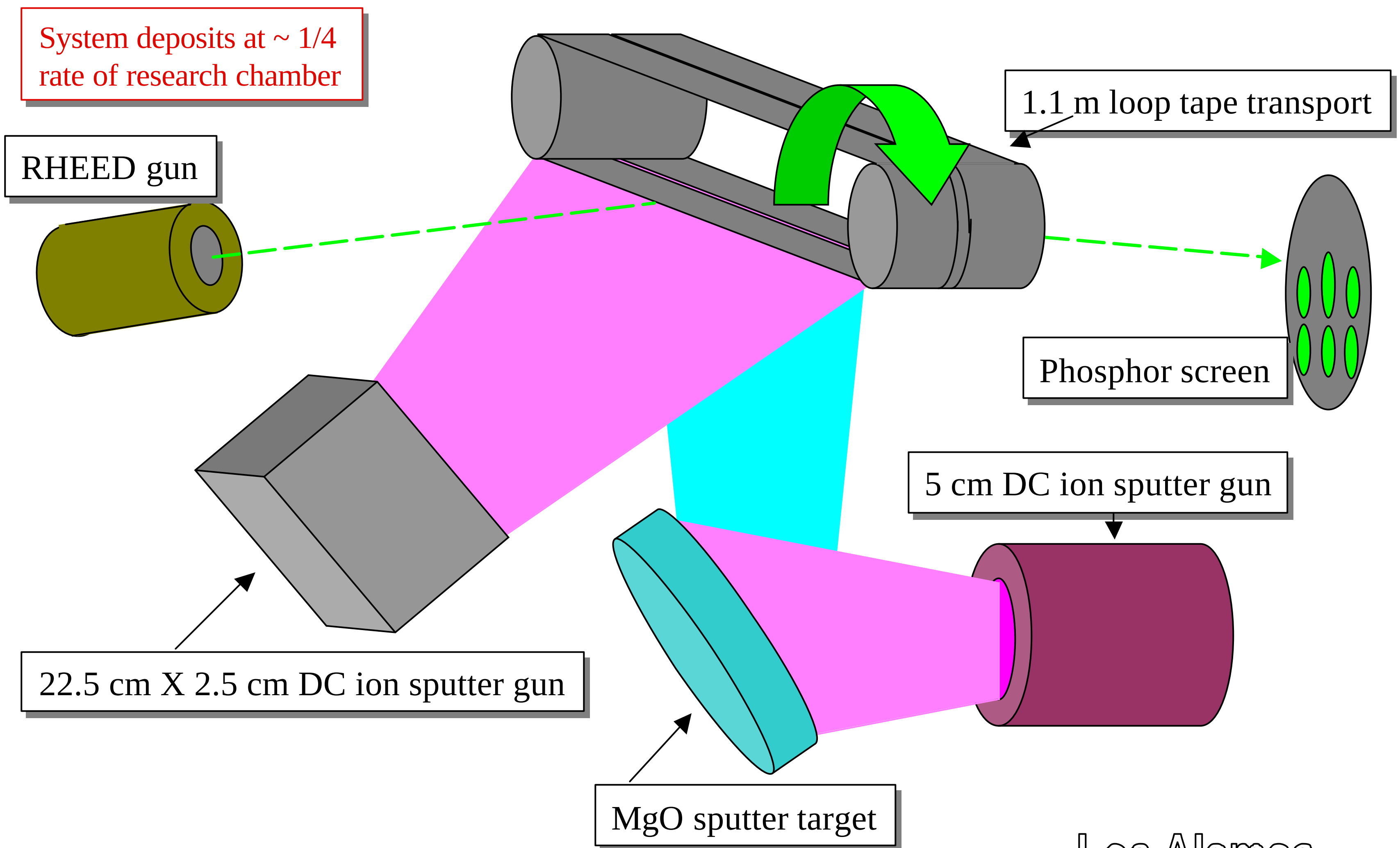
Substrate roughness must be minimized to optimize YBCO/I BAD MgO texture



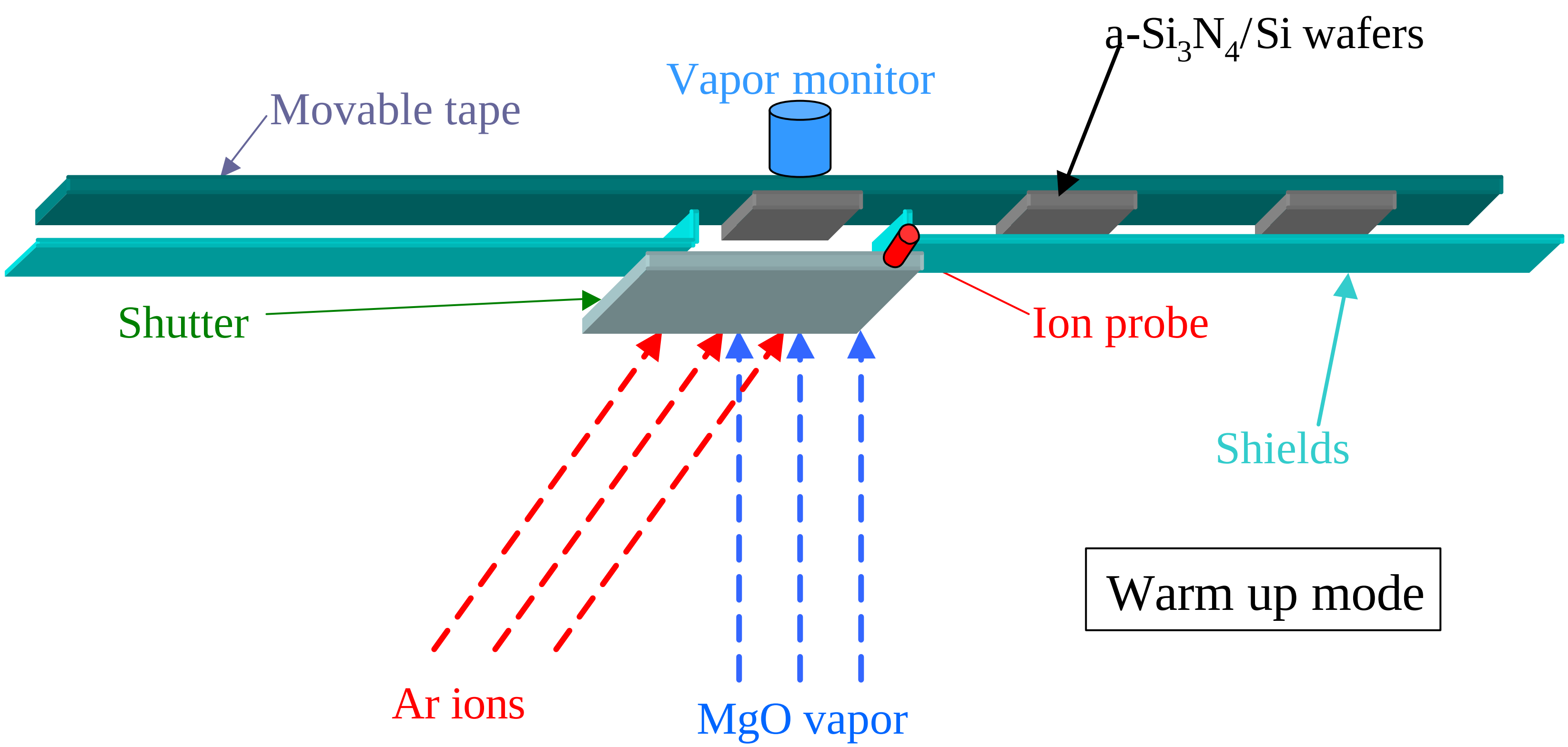
*5 x 5 μm AFM scan area

YBCO/CeO_2/YSZ/h-MgO/IBAD MgO/ a-Si_3N_4/bp-C276

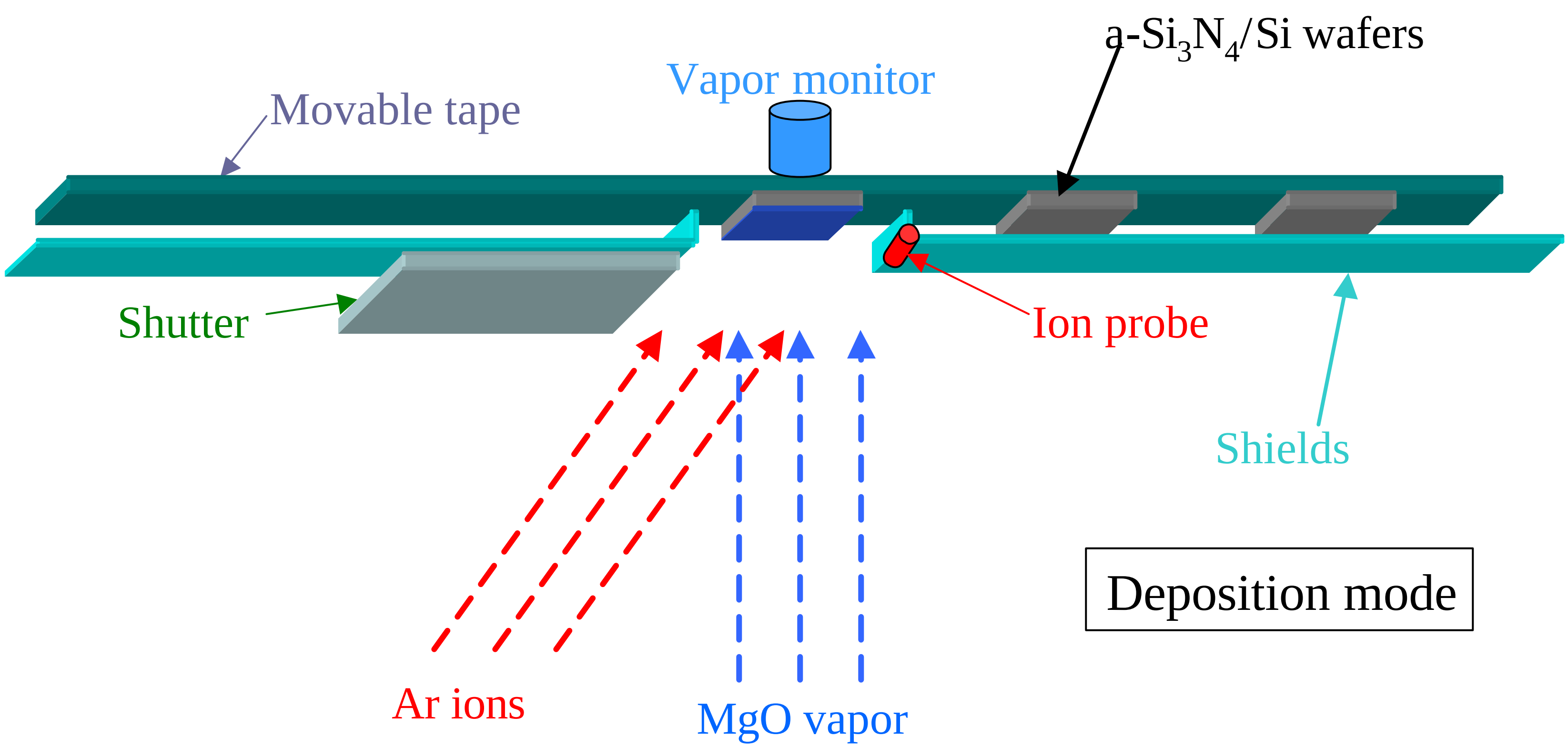
Transfer of batch process parameters to loop coating system



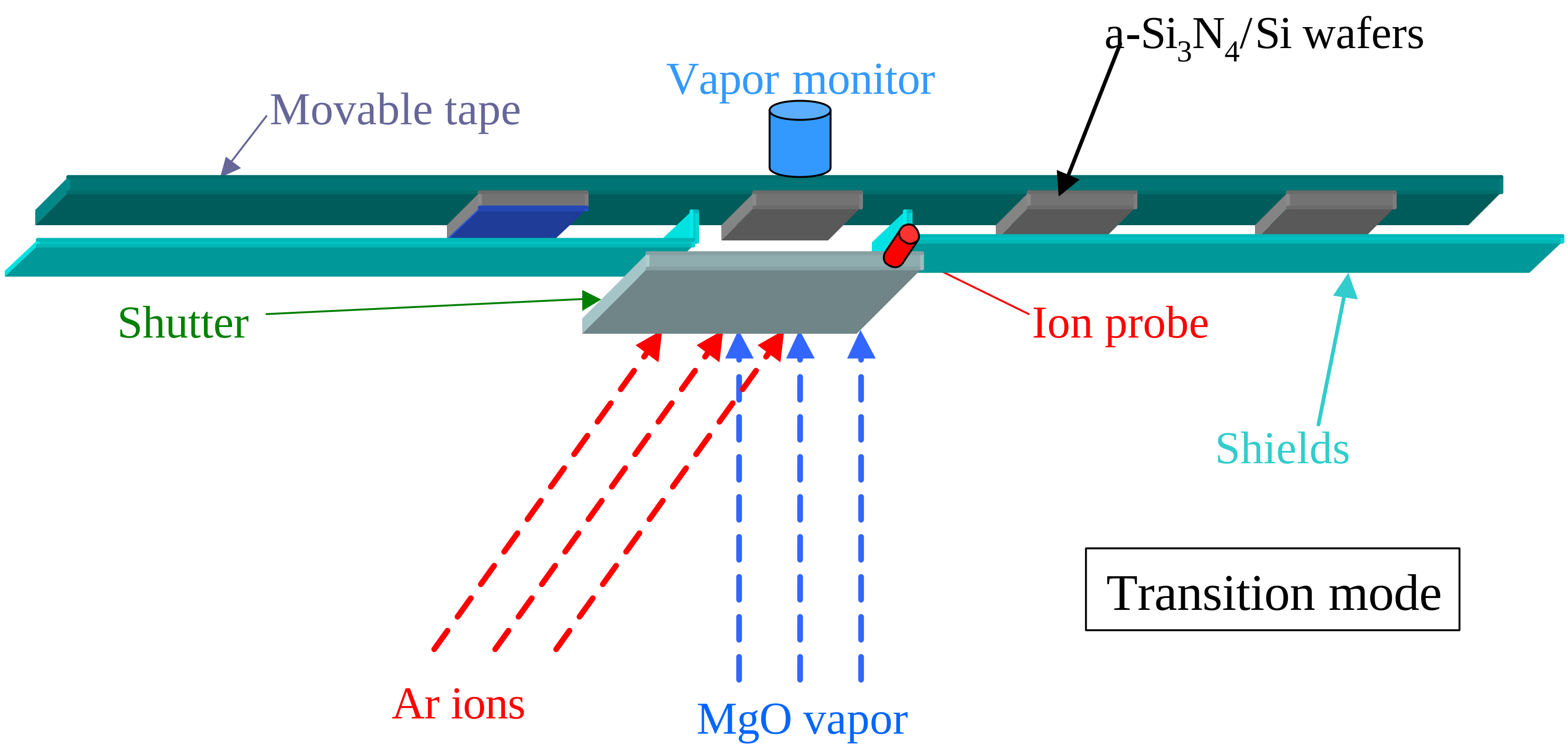
Several experiments to optimize deposition parameters may be performed in one pump down



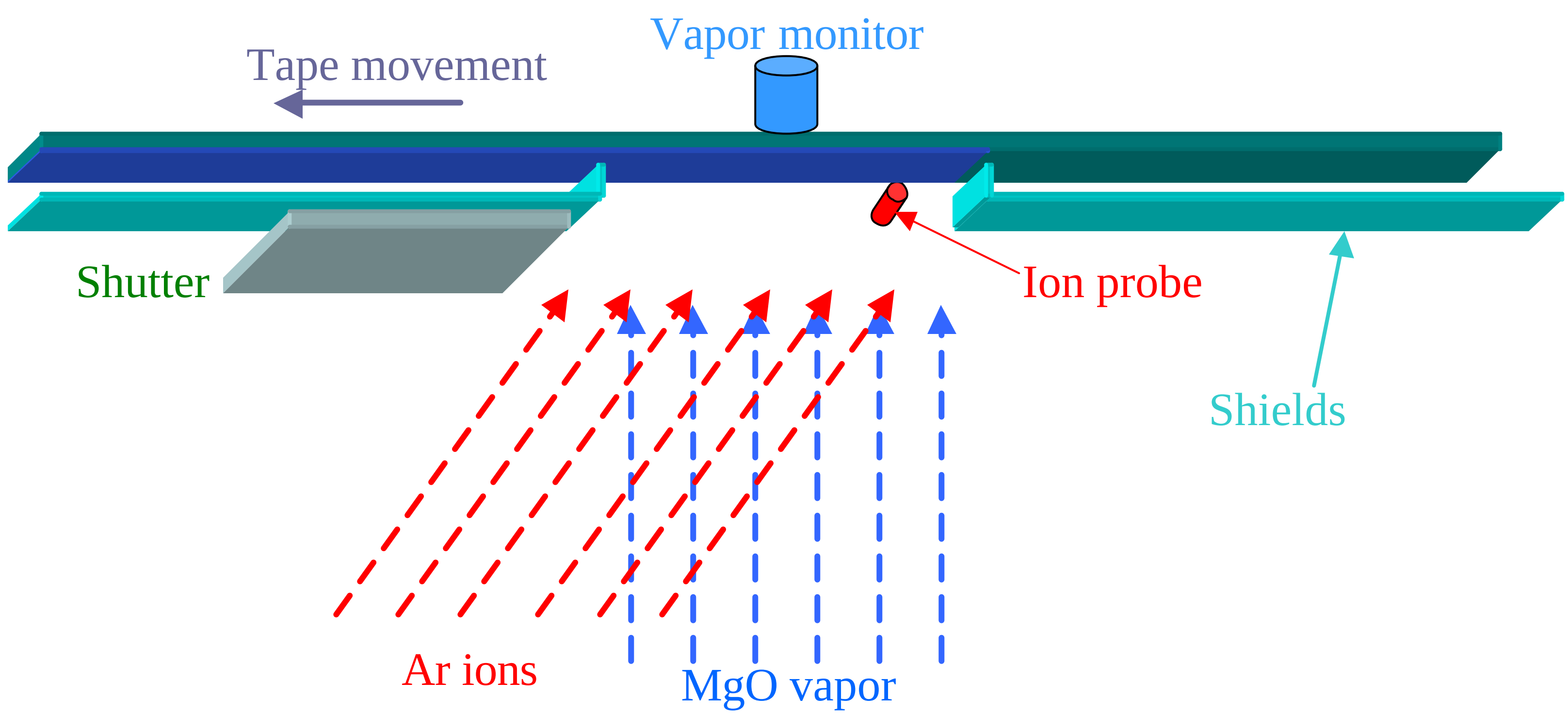
Several experiments to optimize deposition parameters may be performed in one pump down



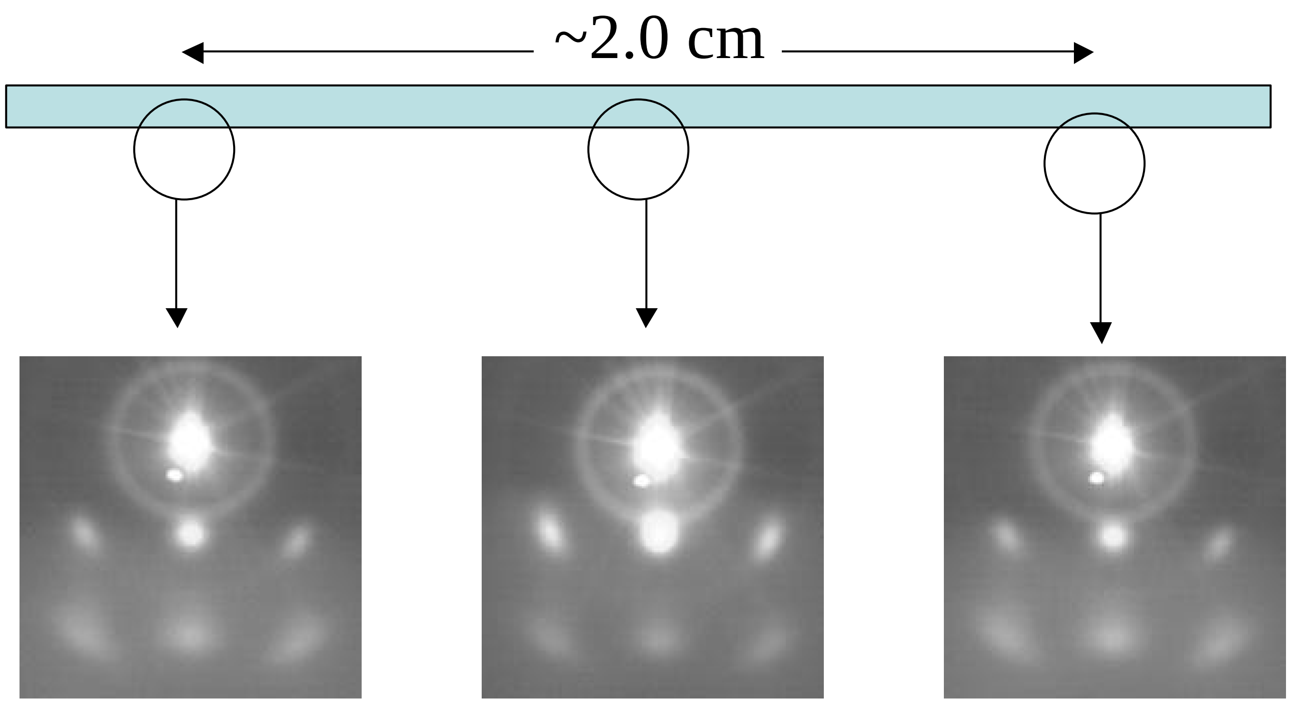
New substrate is brought into position and deposition parameters are changed



Tape coating mode - shields separated further to accommodate wider deposition zone



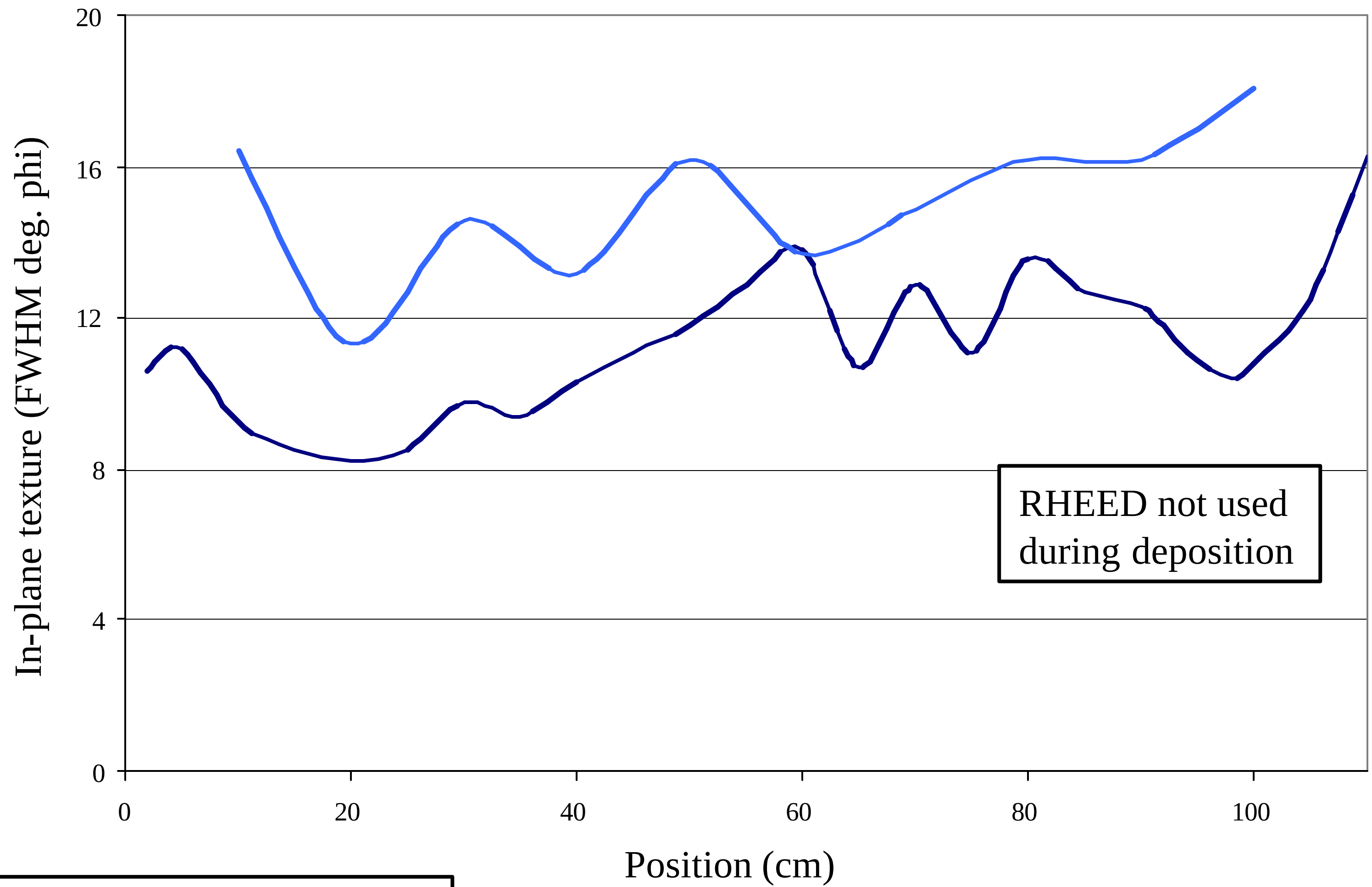
RHEED images may be obtained during continuous processing of tape



Beam sweep less than width of deposition window (~10 cm)

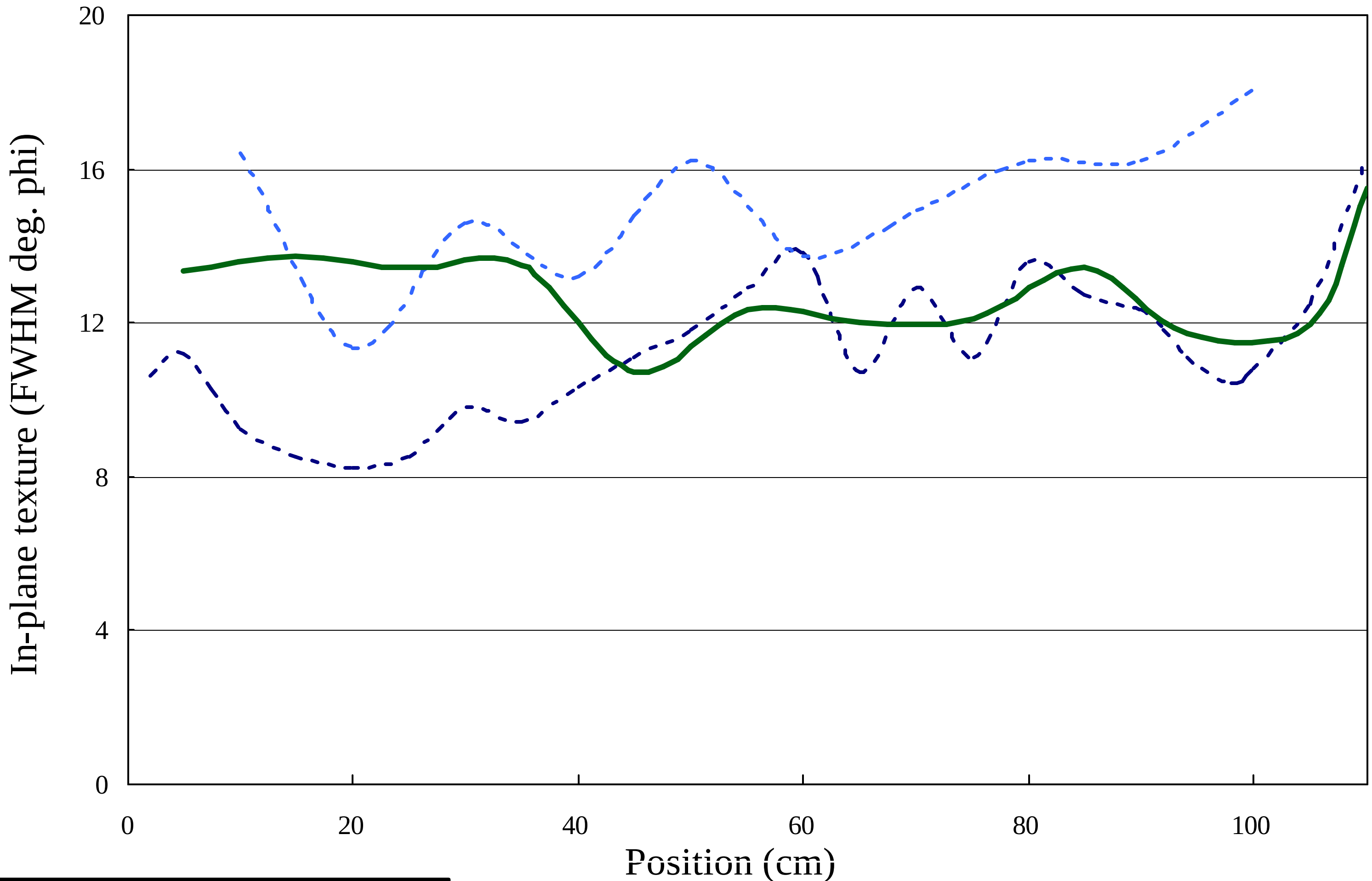
Tape movement causes RHEED pattern fluctuations

IBAD MgO texture variations of first two continuously processed tapes



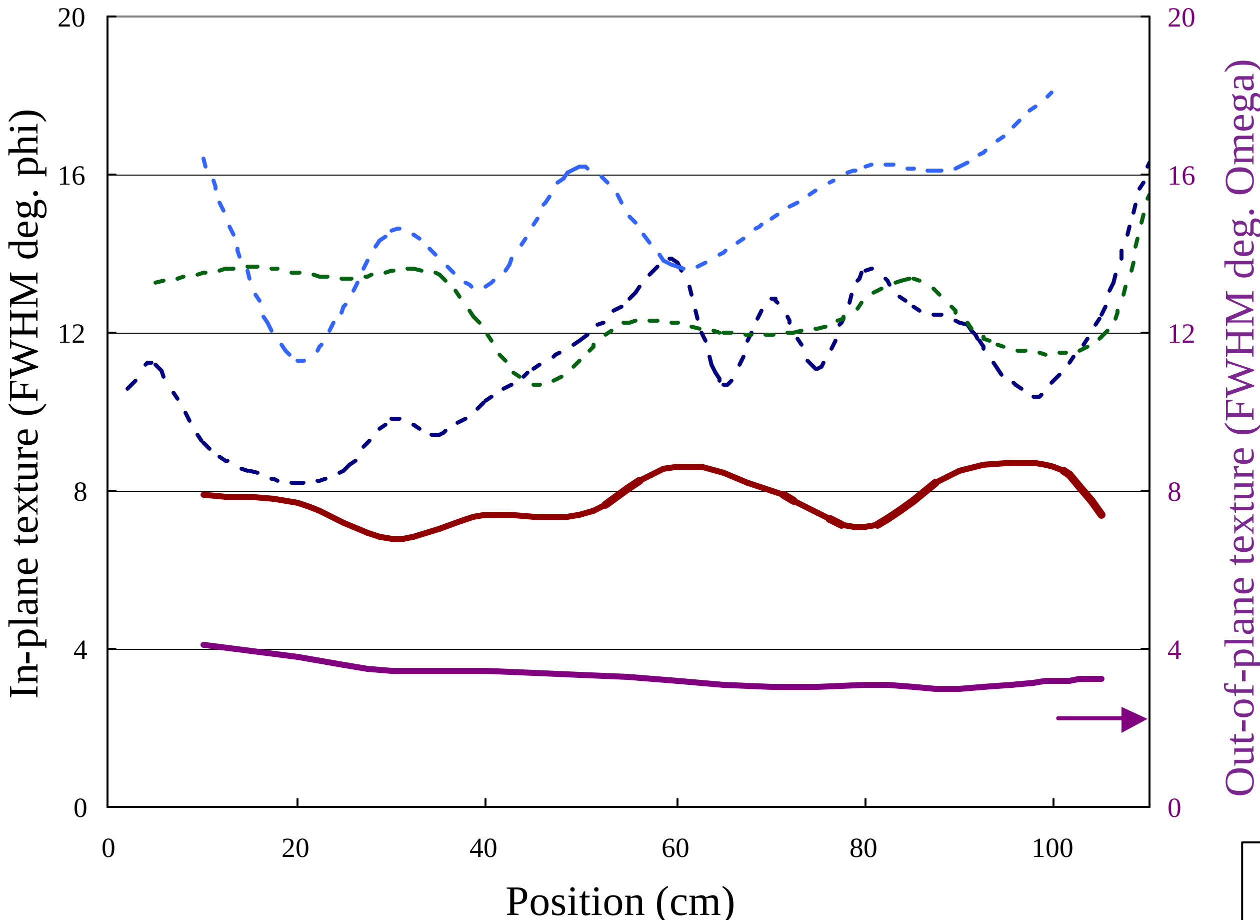
homoepi-MgO/IBAD MgO/ a-Si_3N_4/rp-I625

IBAD MgO texture variations improved using two passes through the deposition zone



homoepi-MgO/IBAD MgO/ a-Si_3N_4/rp-I625

After further refinements* meter long IBAD MgO/I-625 tapes exhibited improved texture uniformity and repeatability

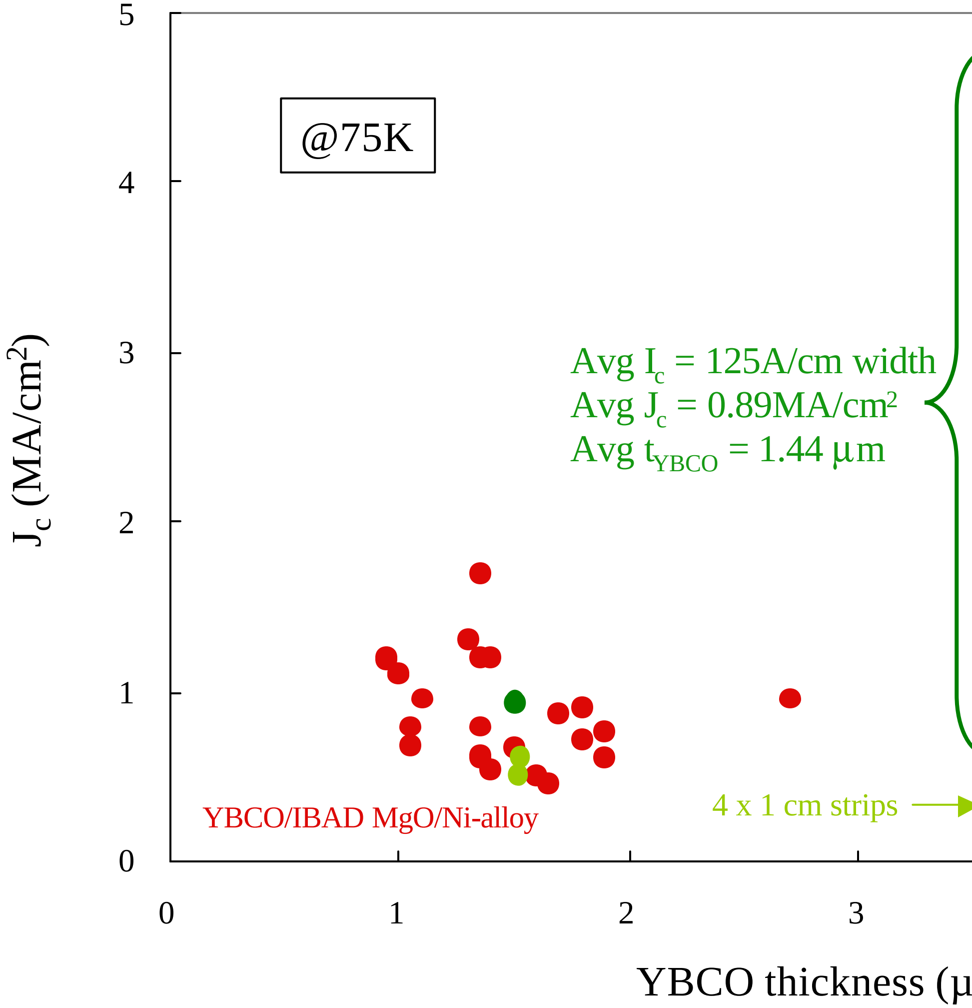


? ? ? . ΔΦ of most recent meters
9.8
8.1
7.8
9.3
9.2
7.8
8.6
9.3

*Ion and vapor fluences held within ± 2 % of "optimum"

homoepi-MgO/IBAD MgO/ a-Si_3N_4/rp-I625

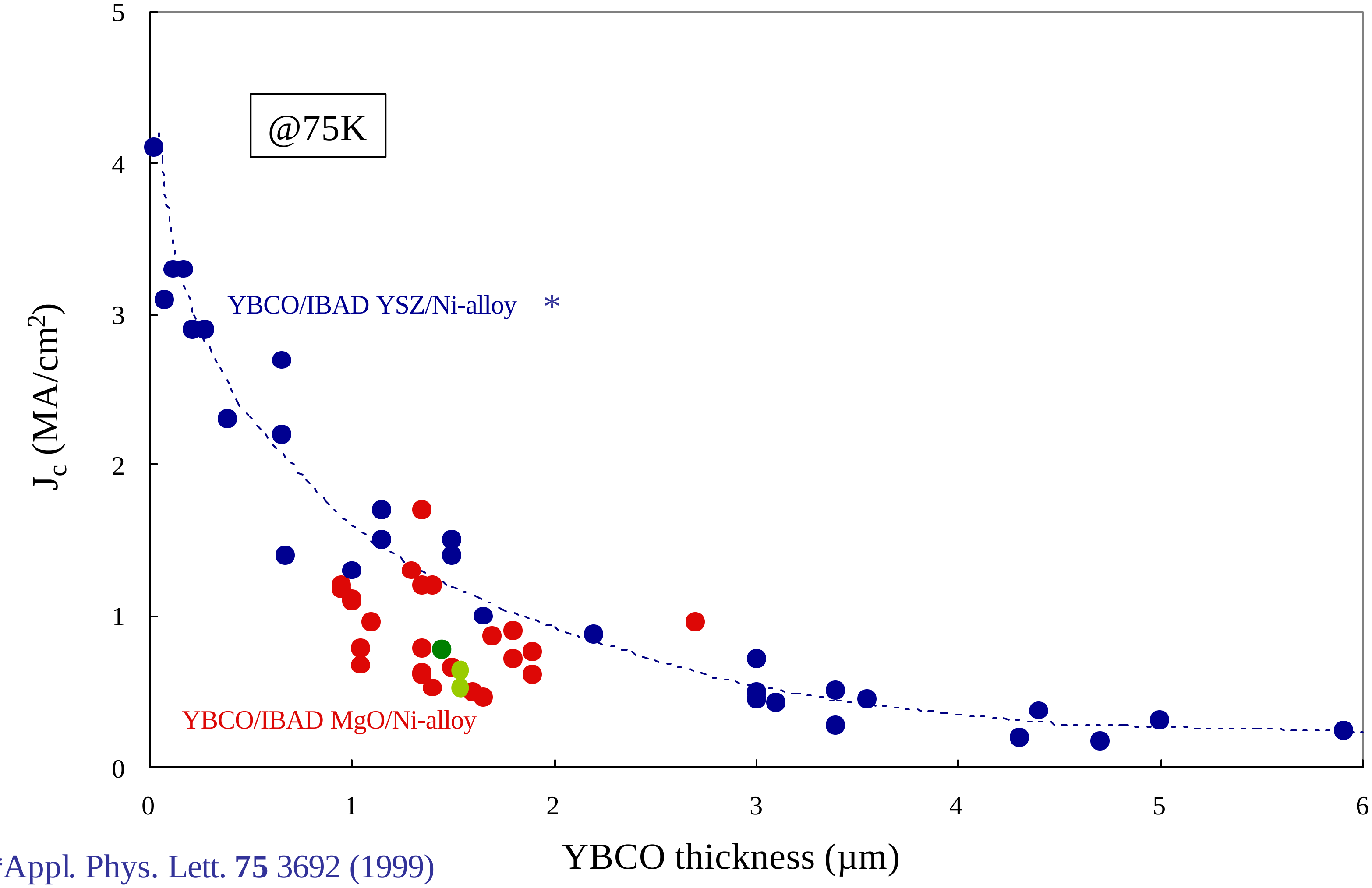
Our last 24 YBCO microbridges on a continuously processed IBAD MgO meter show good I_c and J_c performance



I_c (A/cm)	J_c (MA/cm²)	YBCO Thickness (mm)
71	0.68	1.05
74	0.53	1.4
76	0.46	1.65
80	0.5	1.6
82	0.61	1.35
83	0.79	1.05
85	0.63	1.35
99	0.66	1.5
106	0.96	1.1
107	0.79	1.35
110	1.1	1
111	1.11	1
112	1.18	0.95
114	1.2	0.95
116	0.61	1.9
128	0.71	1.8
146	0.77	1.9
148	0.87	1.7
162	0.9	1.8
162	1.2	1.35
168	1.2	1.4
169	1.3	1.3
230	1.7	1.35
259	0.962	2.7
73	0.49	1.5
93	0.62	1.5

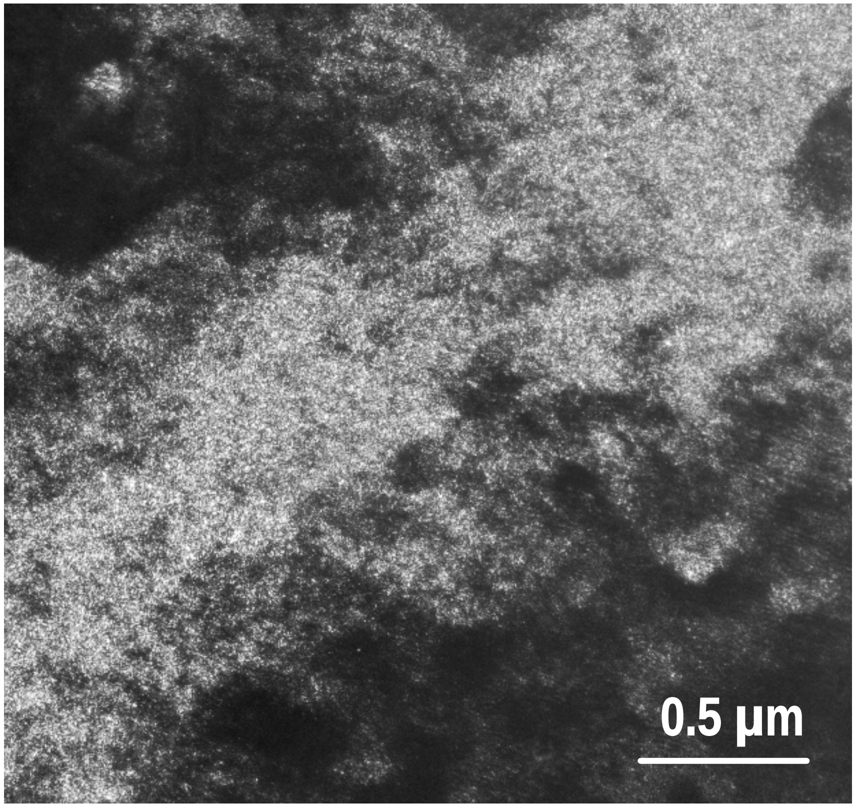
$YBCO/CeO_2/YSZ/h\text{-}MgO/IBAD\ MgO/\ a\text{-}Si_3N_4/rp\text{-}C276$

J_c performance comparison of YBCO microbridges on continuously processed IBAD YSZ and IBAD MgO templates



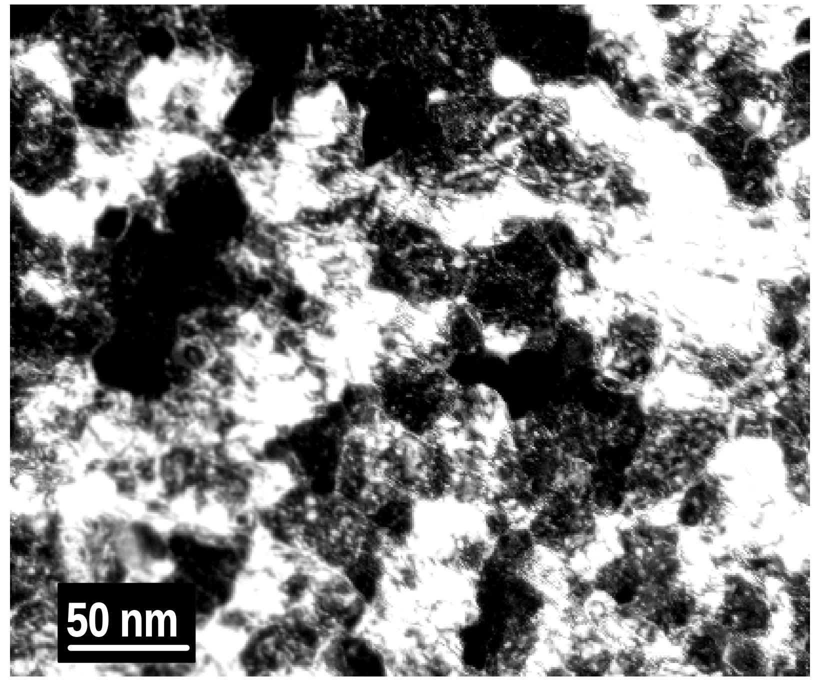
*Appl. Phys. Lett. **75** 3692 (1999)

Plan view dark field TEM reveals microstructural differences between IBAD-YSZ and IBAD-MgO



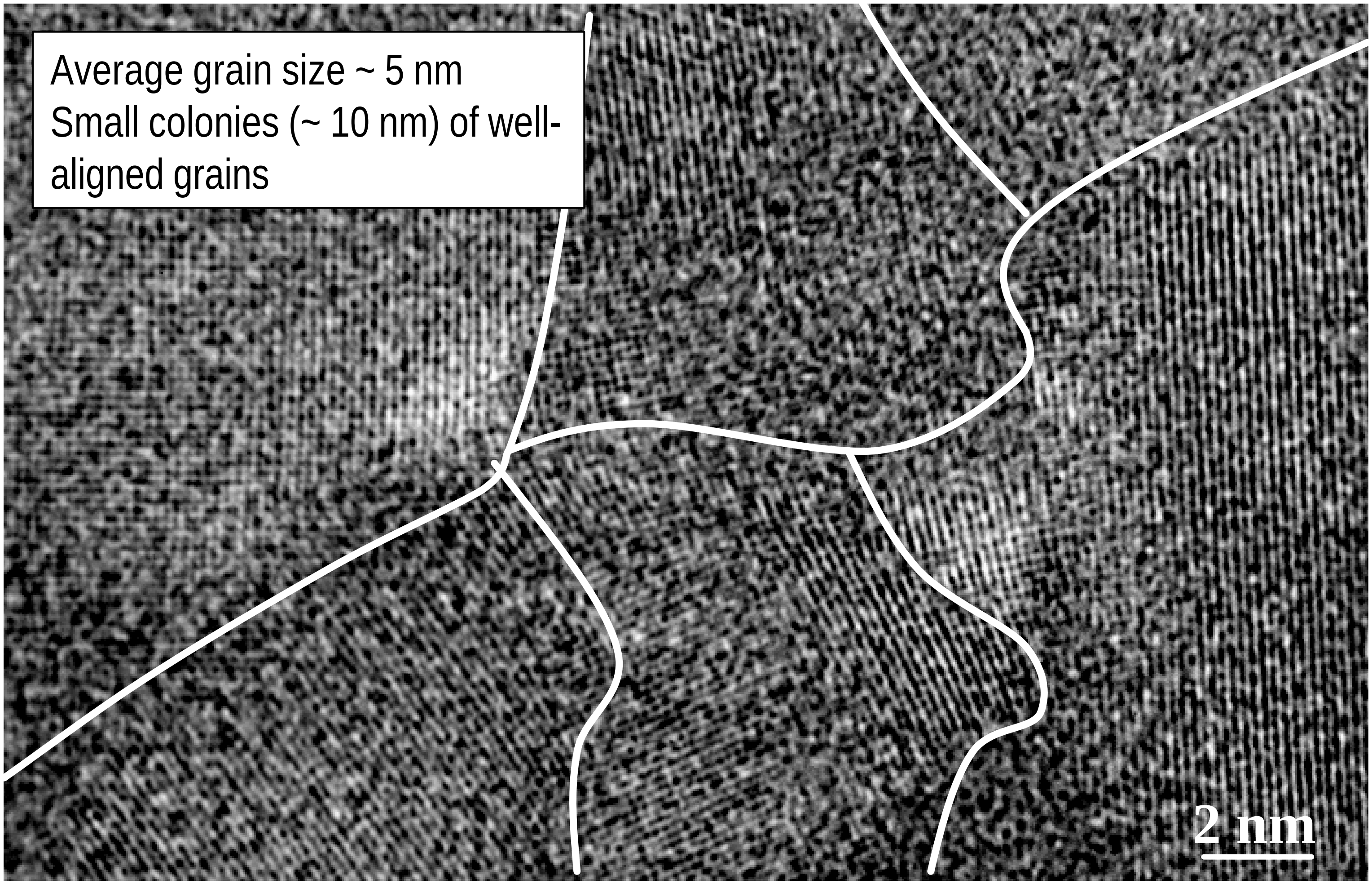
Average sub-grain size ~ 5 nm
Micron sized colony of well-aligned grains

Ion beam sputtered IBAD MgO

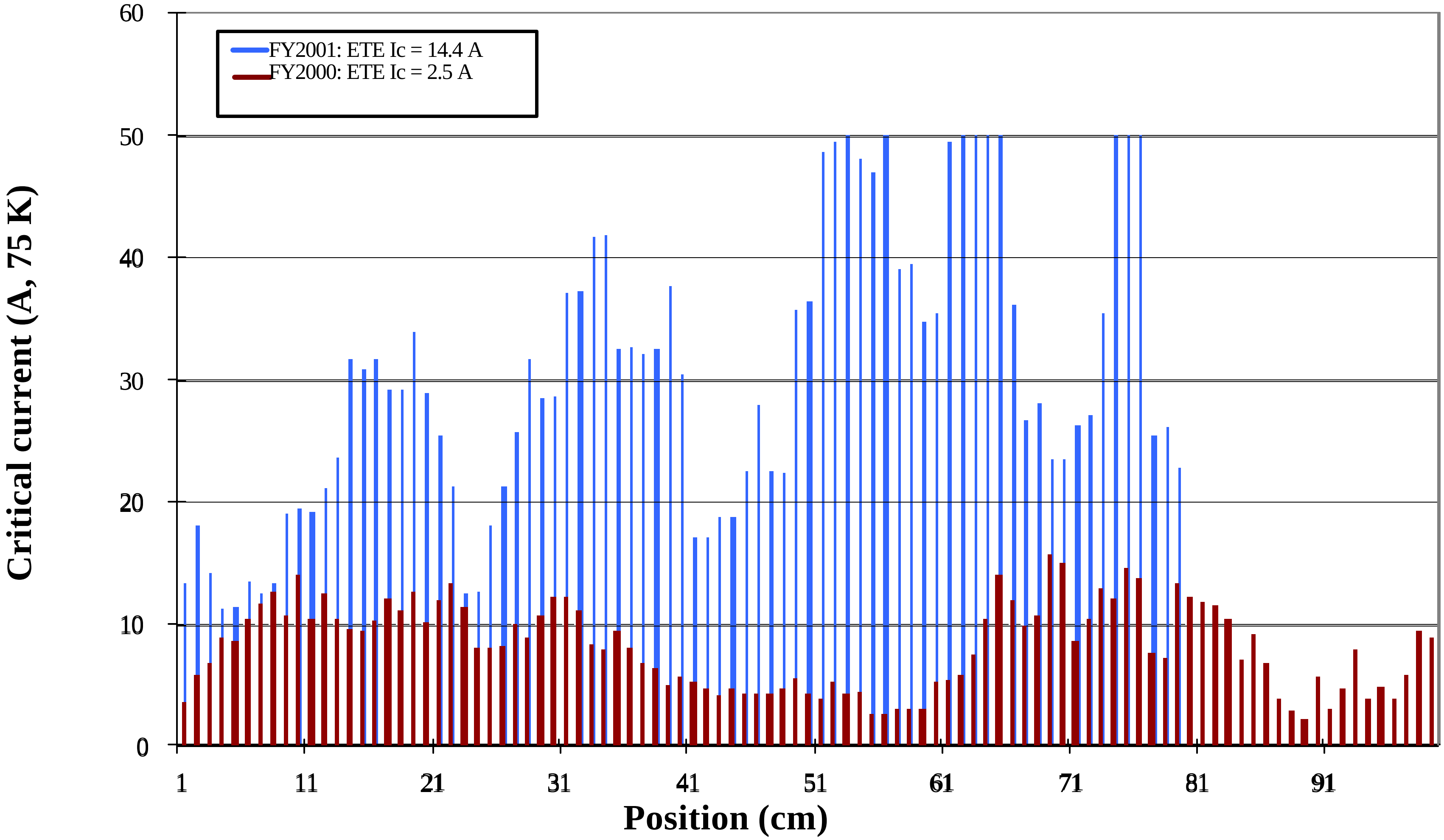


Average grain size ~ 50 nm
Small colony (~ 200 nm) of well-aligned grains

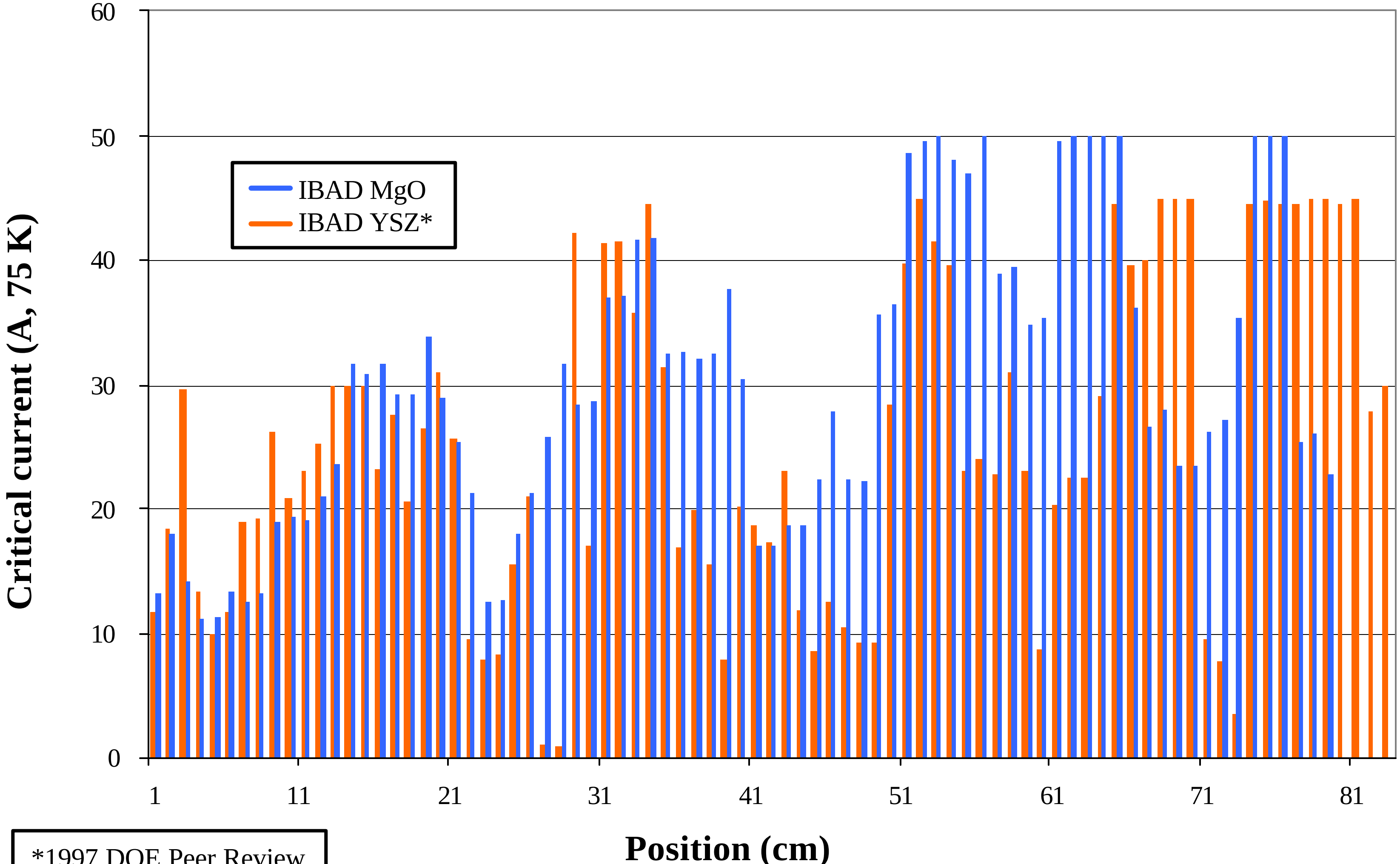
Plan view bright field TEM reveals finer grains and smaller colony size for e-beam evaporated IBAD-MgO



Ic vs. position comparison for YBCO on IBAD MgO templates



Comparable meter length YBCO results achieved at LANL after four years of development with each template



*1997 DOE Peer Review

IBAD MgO Summary

- ➔ RHEED/x-ray diffraction used to optimize deposition parameters for IBAD MgO templates
- ➔ Demonstrated good texture on continuously processed meter lengths of IBAD MgO templates without RHEED (best: $\Delta\phi_{??e} = 7.8°$, $\Delta\omega_{??e} = 3.3°$)
- ➔ Demonstrated run-to-run texture repeatability with average $\Delta\phi \sim 8.8°$ over meter lengths (FY2000: $\Delta\phi_{??e} \sim 20°$)
- ➔ Using continuously processed IBAD MgO produced: 24 bridge samples with $Ic_{??e}$(75K) = 125 A/cm width, $Jc_{??e}$(75K) = 0.89 MA/cm^2; 4 x 1 cm samples with best Ic(75K) = 93 A
- ➔ Best YBCO/IBAD MgO tape result: Ic(75K) = 14.4 A (80 cm length)

Future issues:

- Improve performance of YBCO/IBAD MgO meters to be comparable to that of YBCO/IBAD YSZ meters
- Simplify buffer layer stack
- Demonstrate < 5 minute/meter deposition time for IBAD MgO
- Investigate non-RHEED methods for optimizing IBAD MgO

High current coated conductors based on IBAD YSZ and thick YBCO / Sm-123 multilayers

S.R. Foltyn, Q.X. Jia, P.C. Dowden, P.N. Arendt,
J.F. Smith, T.G. Holesinger, H. Kung, J.Y. Coulter,
B.J. Gibbons, D.B. Jan, R.F. DePaula, L. Stan, J.R. Groves

Los Alamos National Laboratory
Superconductivity Technology Center
Los Alamos, New Mexico

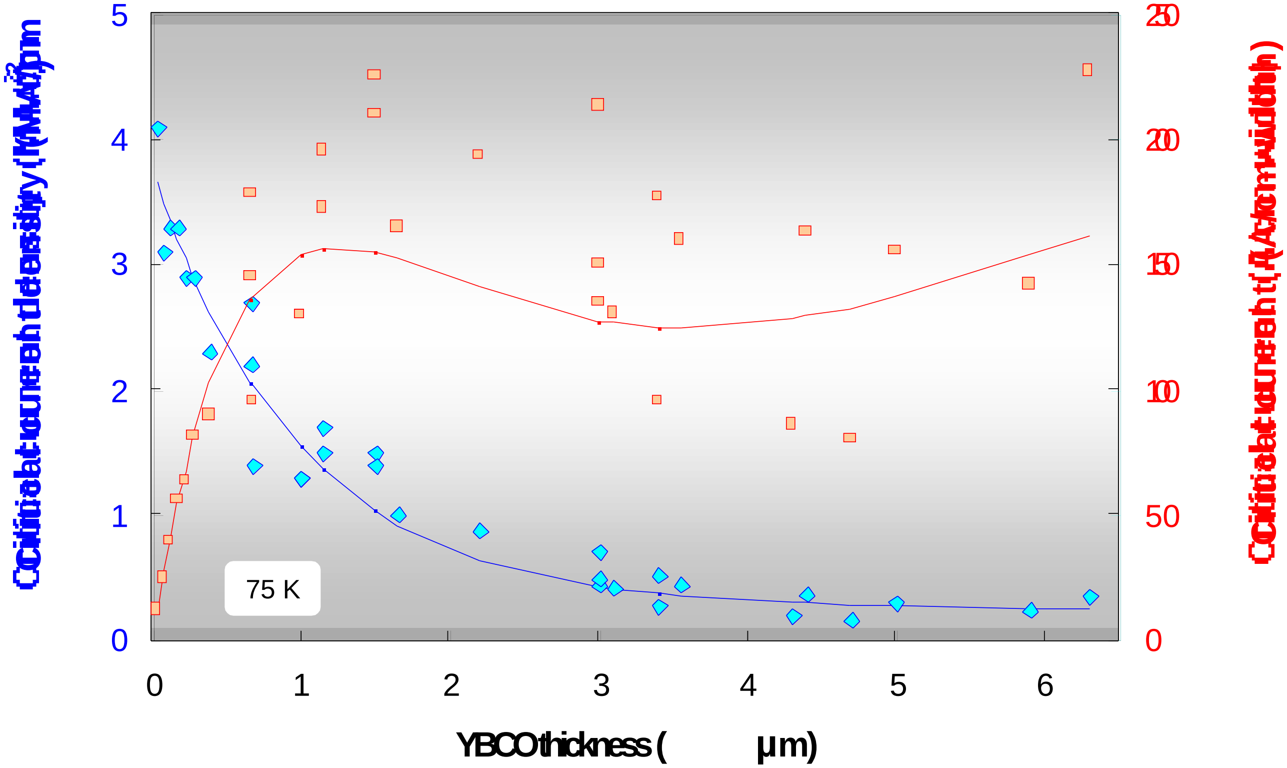
Research on thick YBCO is important for several reasons

- Retain high current in a magnetic field at liquid nitrogen temperature
  - 100 A/cm-width at 1 T (B||c) requires >500 A/cm in self field
- Achieve high J_e at liquid nitrogen temperature
  - 100,000 A/cm^2 requires I_c >500 A/cm on 50 μm thick substrates
- Explore the limits of coated conductor technology

Previously we showed that a tape current "limit" of about 200 A/cm-width was reached at a YBCO thickness of ~1.5 microns

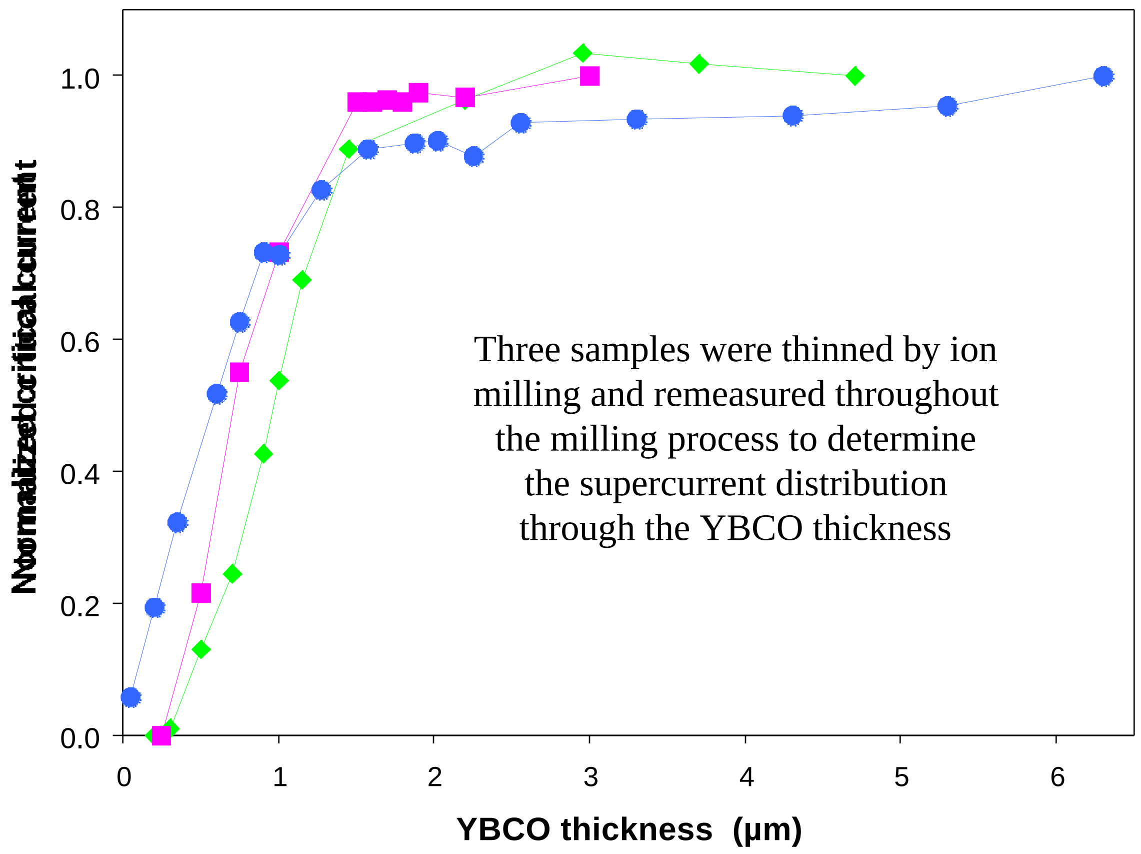
PLD YBCO on Inconel substrates with Y_2O_3- or CeO_2-buffered IBAD YSZ

Bridge dimensions: ~200 µm x 5 mm



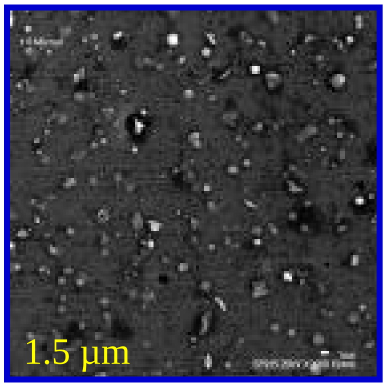
Appl. Phys. Lett. **75**, 3692 (1999)

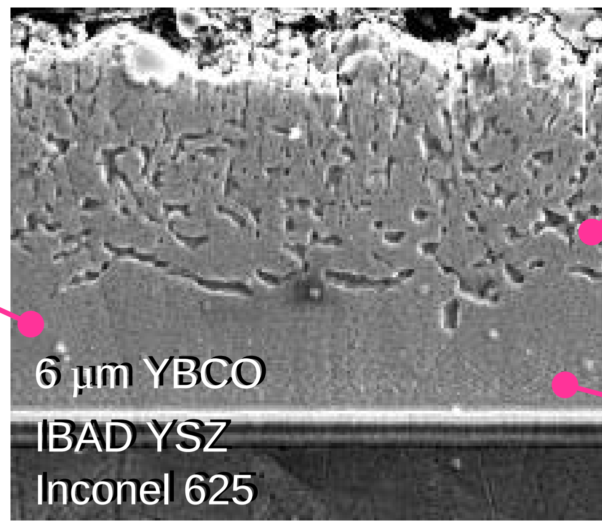
Ion milling experiments revealed that little or no current was carried in the top layers

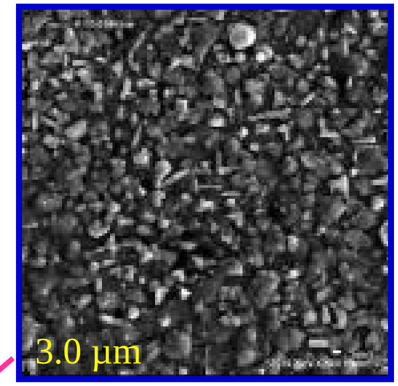


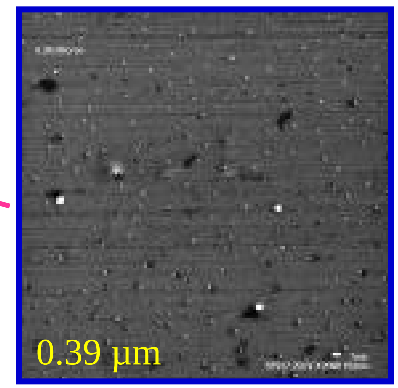
The problem at levels above 1.5 µm appears to be related to roughness-induced porosity as the YBCO becomes thicker

SEM plan views (2000x) show increased roughening with thickness, which leads to the poor connectivity shown in SEM cross-section

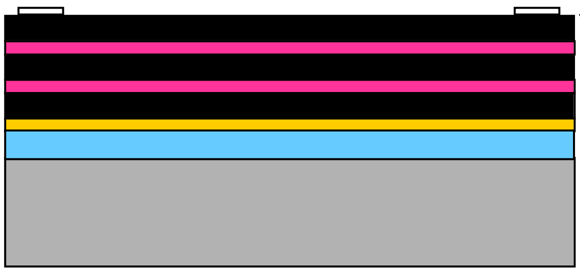


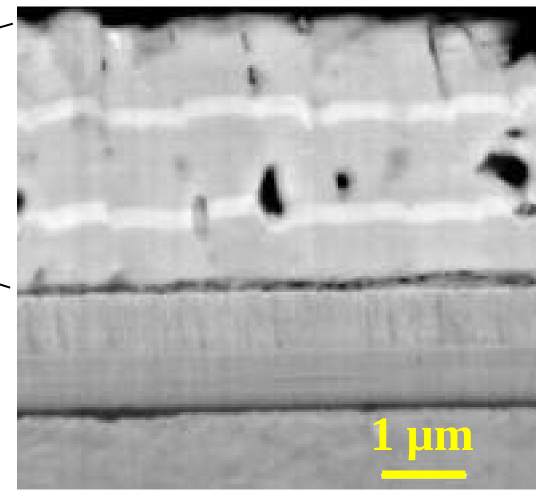






In an attempt to “reset” the YBCO morphology, we used interlayers of Sm-123, which by itself yields very smooth coatings with low J_c





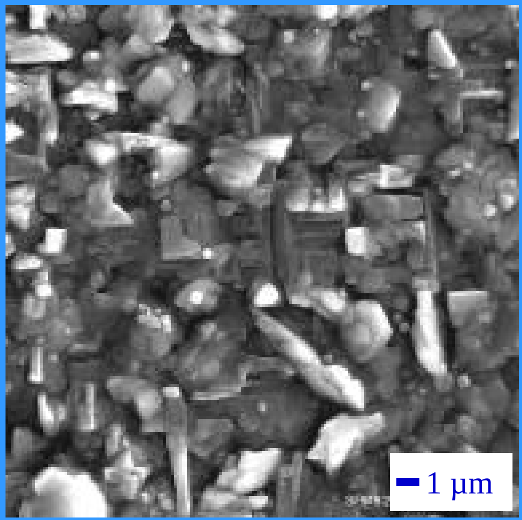
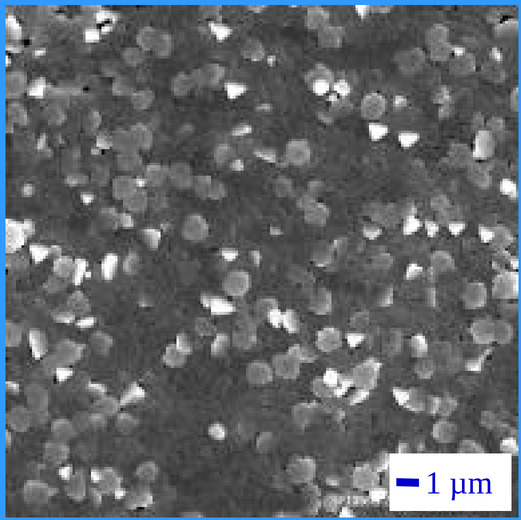
- Silver contact
- YBCO
- $Sm_1Ba_2Cu_3O_{7-\delta}$
- CeO_2
- IBAD YSZ
- Inconel

Y - Sm - Y - Sm - Y multilayer

YBCO thickness: ~1.0 µm

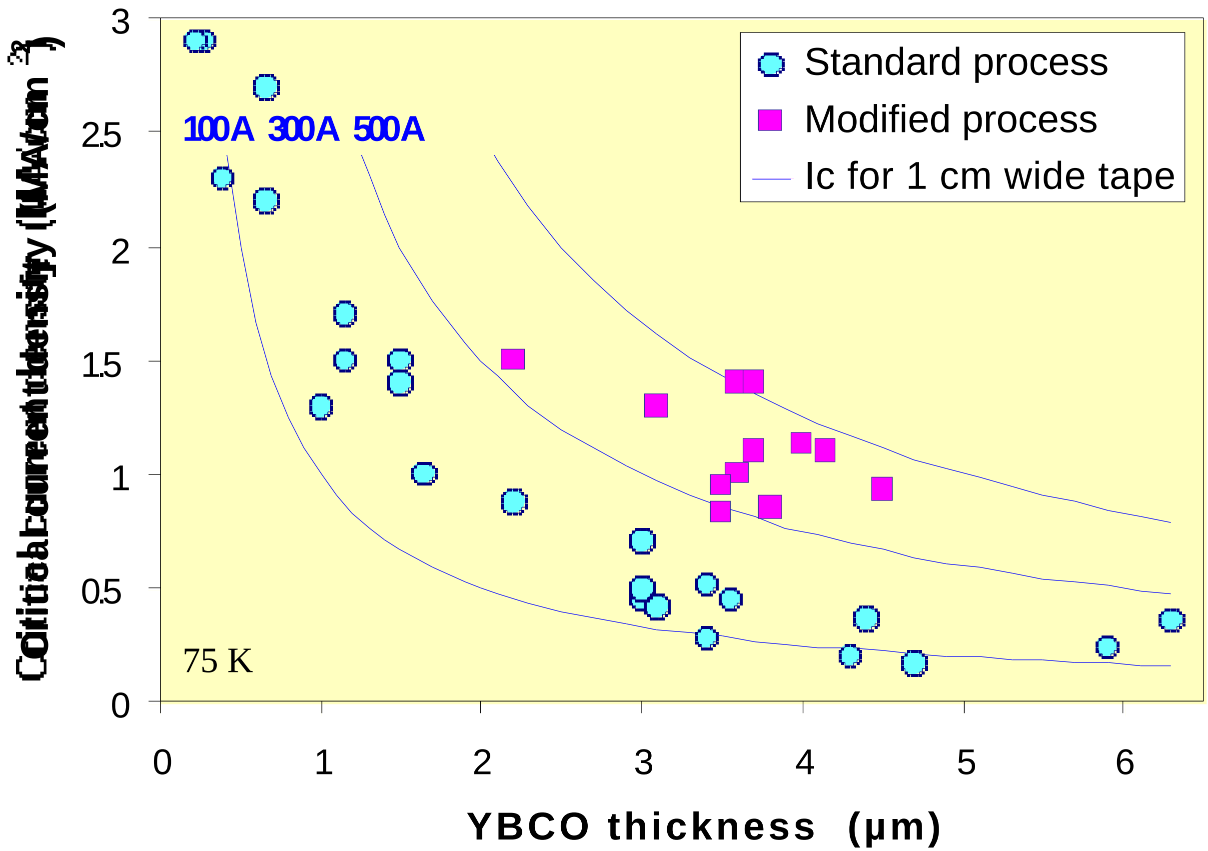
SBCO thickness: ~ 0.2 µm

The multilayer approach produces a relatively smooth and dense coating and dramatically increases thick film J_c

3.0 µm YBCO standard process	3.7 µm Y/Sm multilayer
	
J_c = 0.6 MA/cm^2	J_c = 1.1 MA/cm^2
I_c = 180 A/cm-width	I_c = 405 A/cm-width

Y/Sm-123 multilayers have allowed us to overcome the 200 A "barrier", as described at the Peer Review last year

Substrate: Inconel 625 with IBAD YSZ – Bridge dimensions: ~200 μm x 5 mm



A source of IBAD YSZ was needed in order to continue multilayer research

Problem

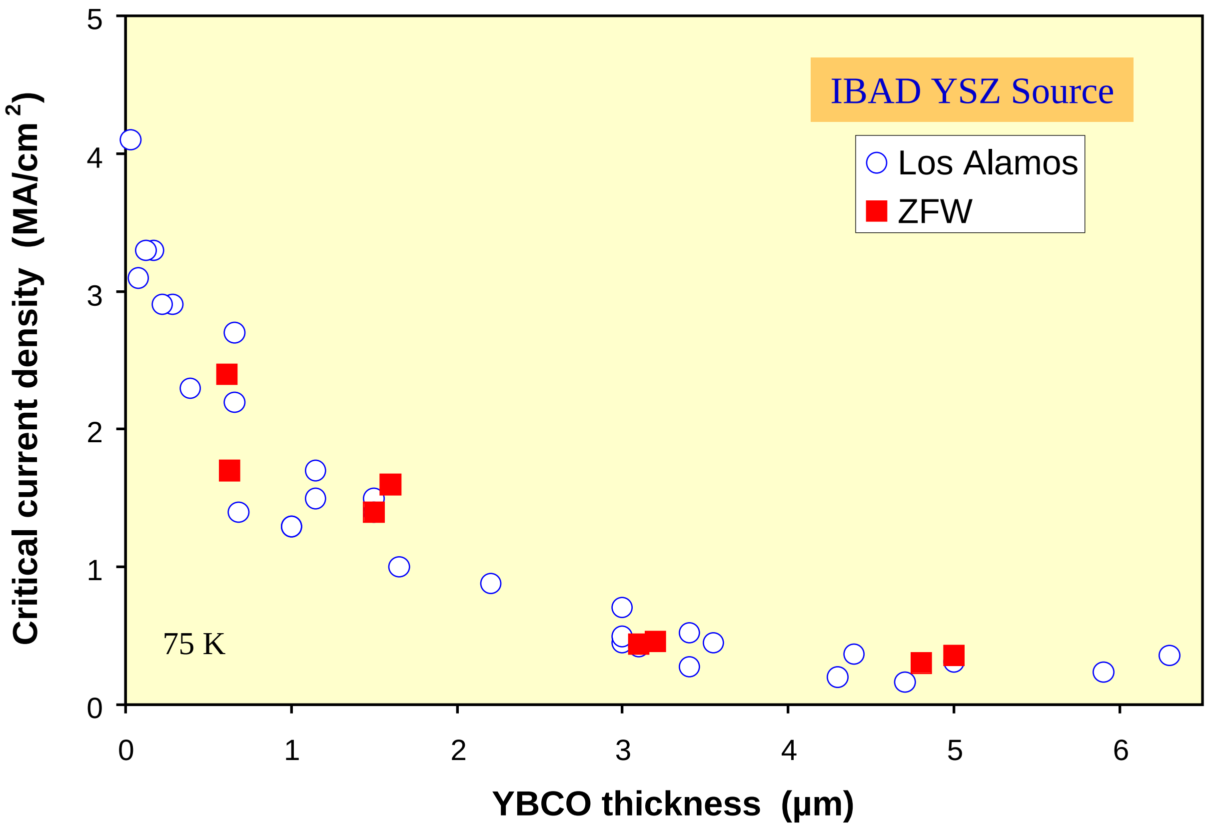
Los Alamos is now focusing exclusively on IBAD MgO template technology, but the YBCO performance achieved with IBAD YSZ has not yet been duplicated with MgO.

Solution

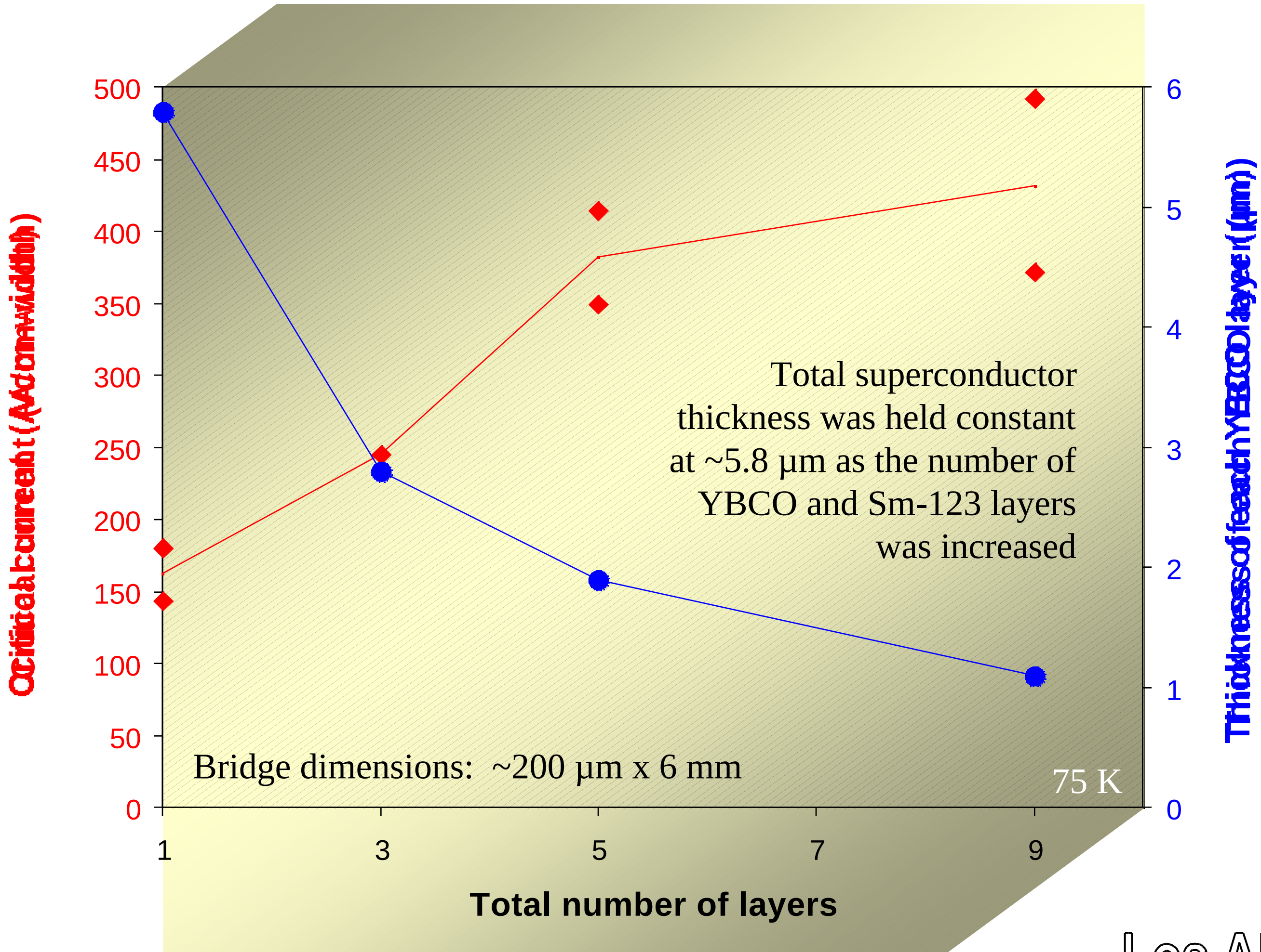
Obtain high-quality IBAD YSZ. Source: Center for Applied Materials Development (ZFW), in Göettingen, Germany.

Performance results for YBCO are the same for both IBAD YSZ sources

Standard YBCO single layers with Y_2O_3 or CeO_2 buffer layers and Inconel 625 substrates



At a given total thickness, multilayer I_c increases with the number of layers deposited



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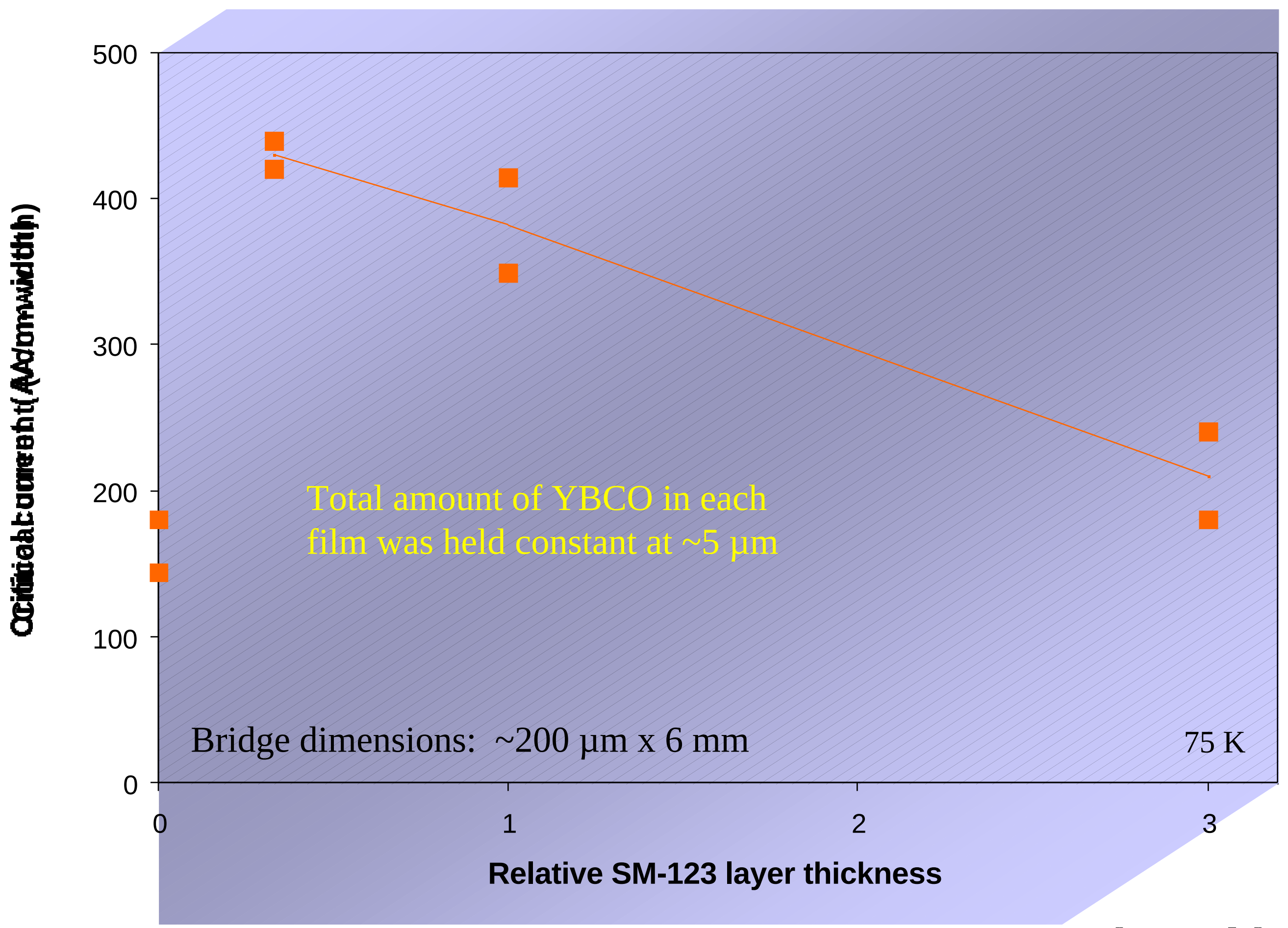
Critical current also depends strongly on the Sm-123 interlayer thickness



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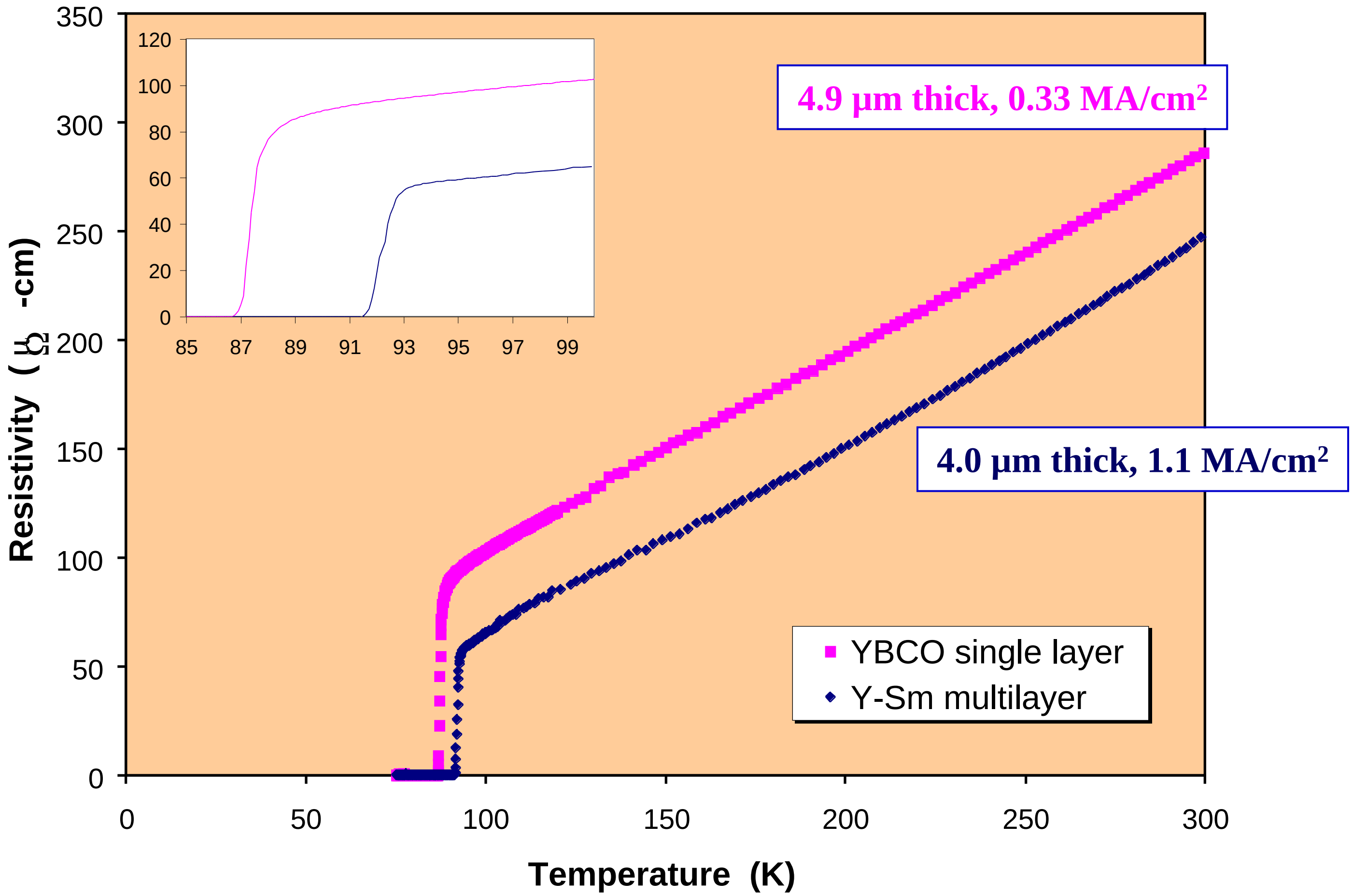
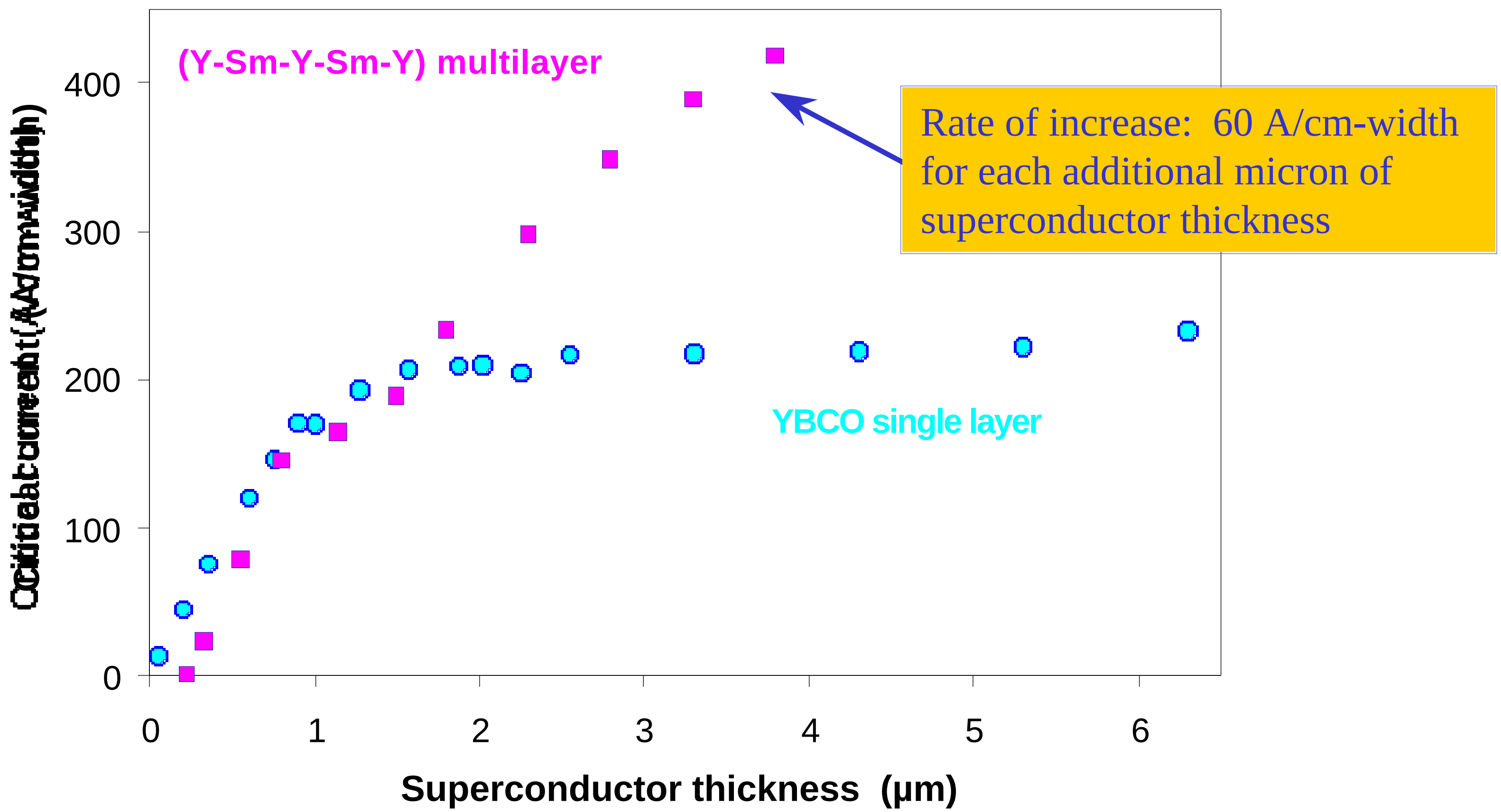
The typical thick multilayer has lower resistivity and higher T_c than a comparable single layer YBCO film



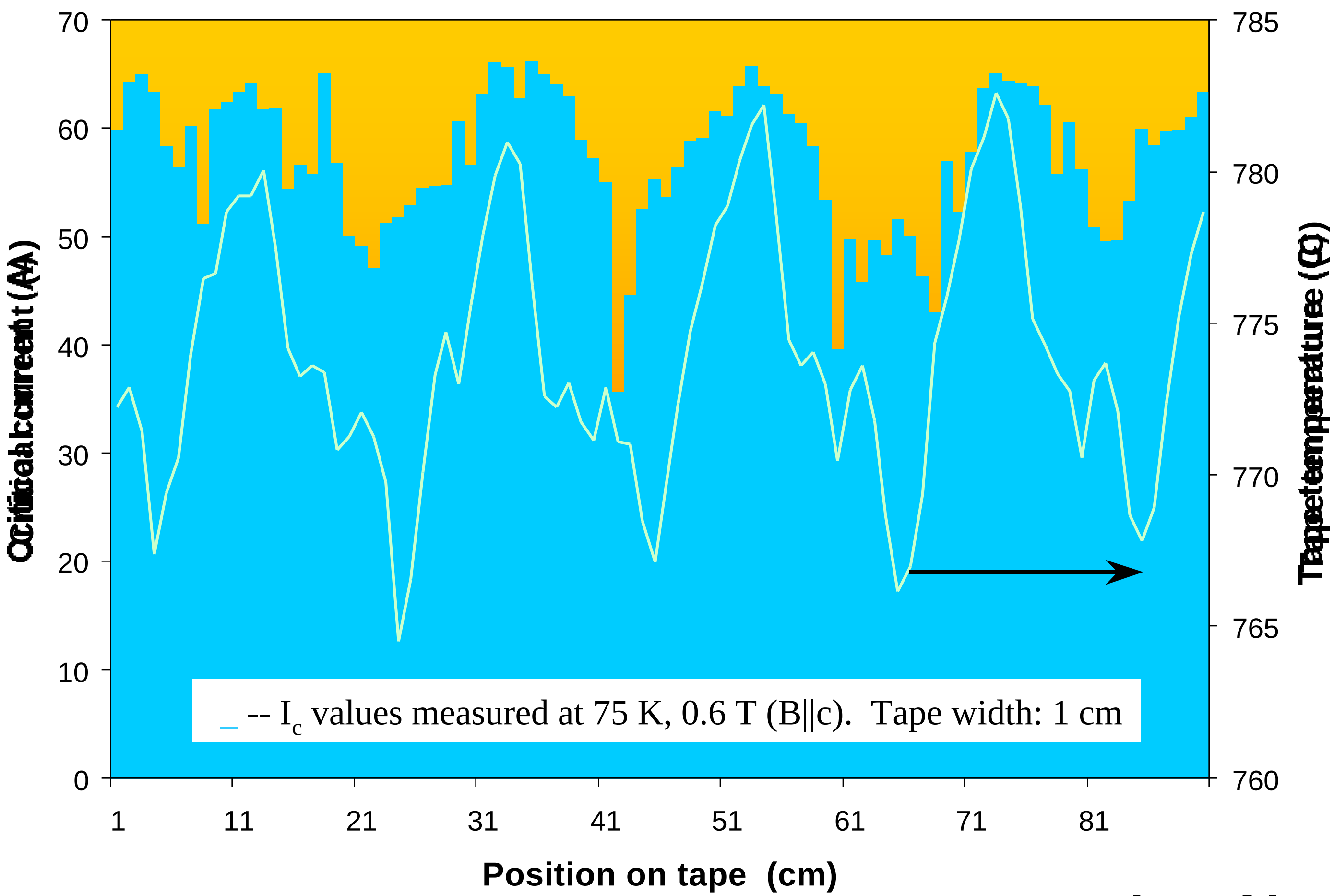
Multilayer performance increase is due mainly to improvement of connectivity above a thickness of ~1.5 µm



The multilayer process was transferred to our PLD tape coating chamber

- ★ A conservative 3-layer design (Y-Sm-Y) was used.
- ★ One-meter-long IBAD YSZ tapes from Germany were first coated with CeO_2 by PLD.
- ★ Total superconductor thickness was ~ 2 µm.
- ★ I_c of the first tape was 142 A.

In a second tape, periodic variations in I_c were observed that indicated a problem with deposition temperature



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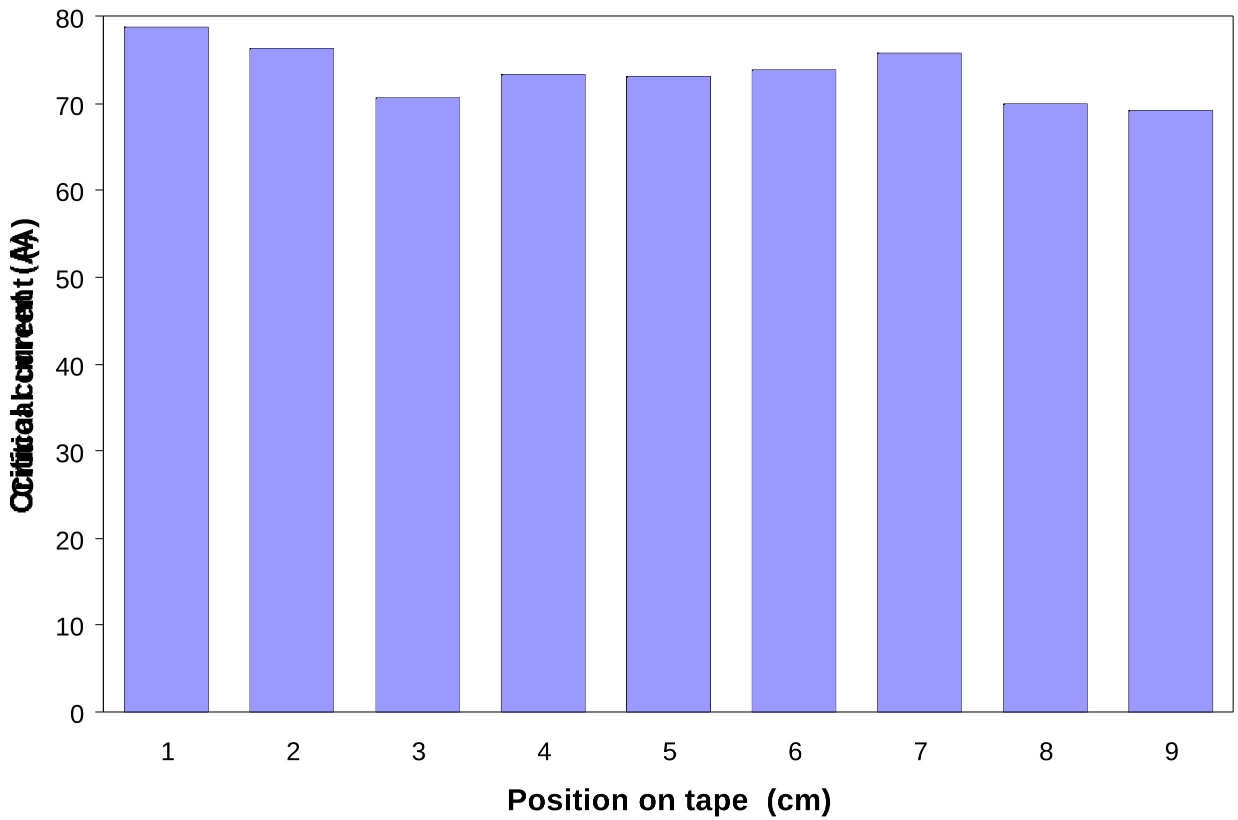
Even with the temperature problem, end-to-end I_c of the tape was at a record level

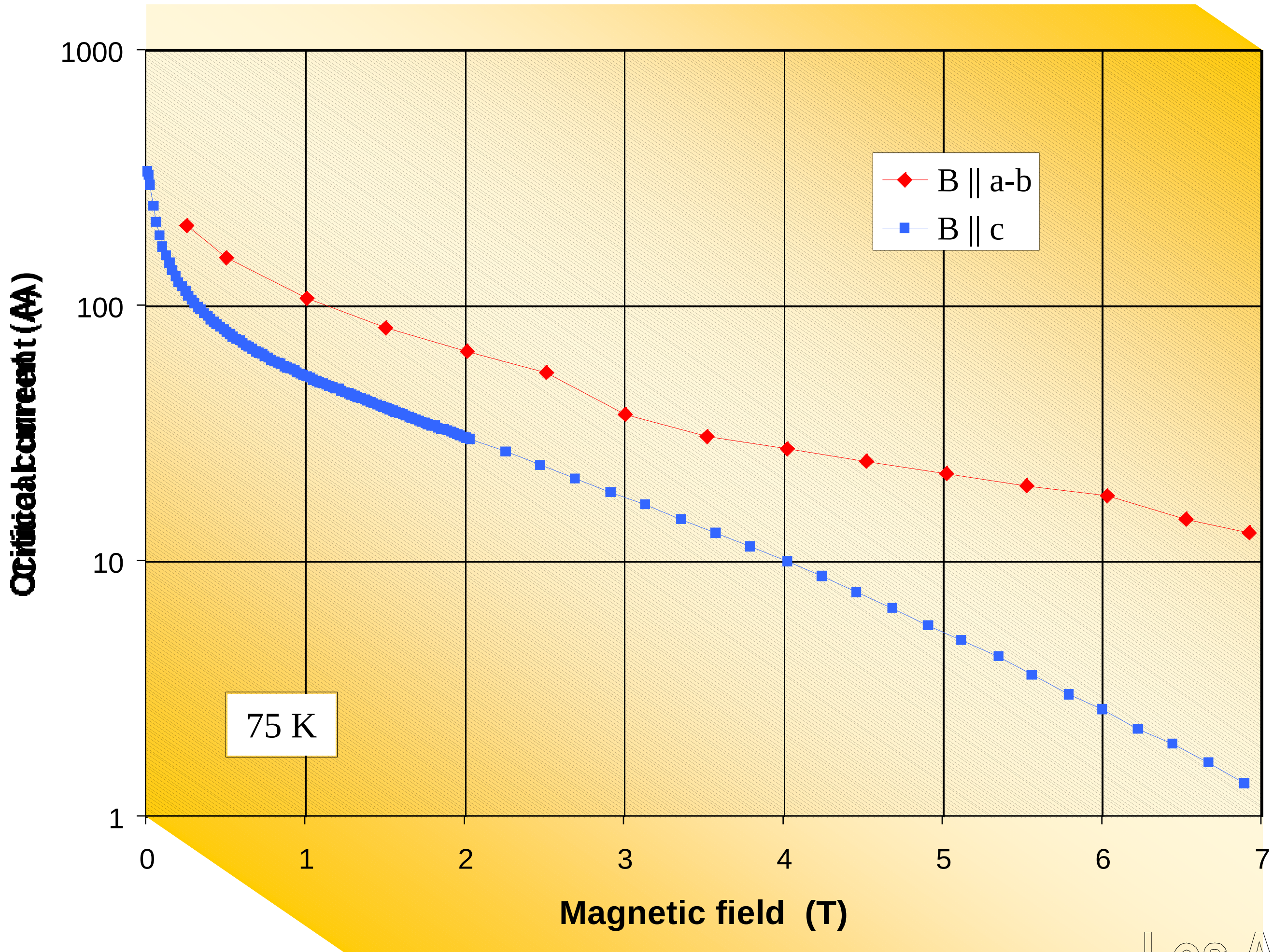
- In self-field, full-length I_c is 189 A (75 K).
- At 0.6 T, lowest valley (determines full-length I_c) is 35 A.
- Peaks in the I_c distribution are at 65 A.
- Self-field I_c of the peak regions should be ~ 350 A.
- Deposition temperature was too low – easily fixed.

Temperature was increased and a 20 cm segment was coated, resulting in 9 cm of measurable length

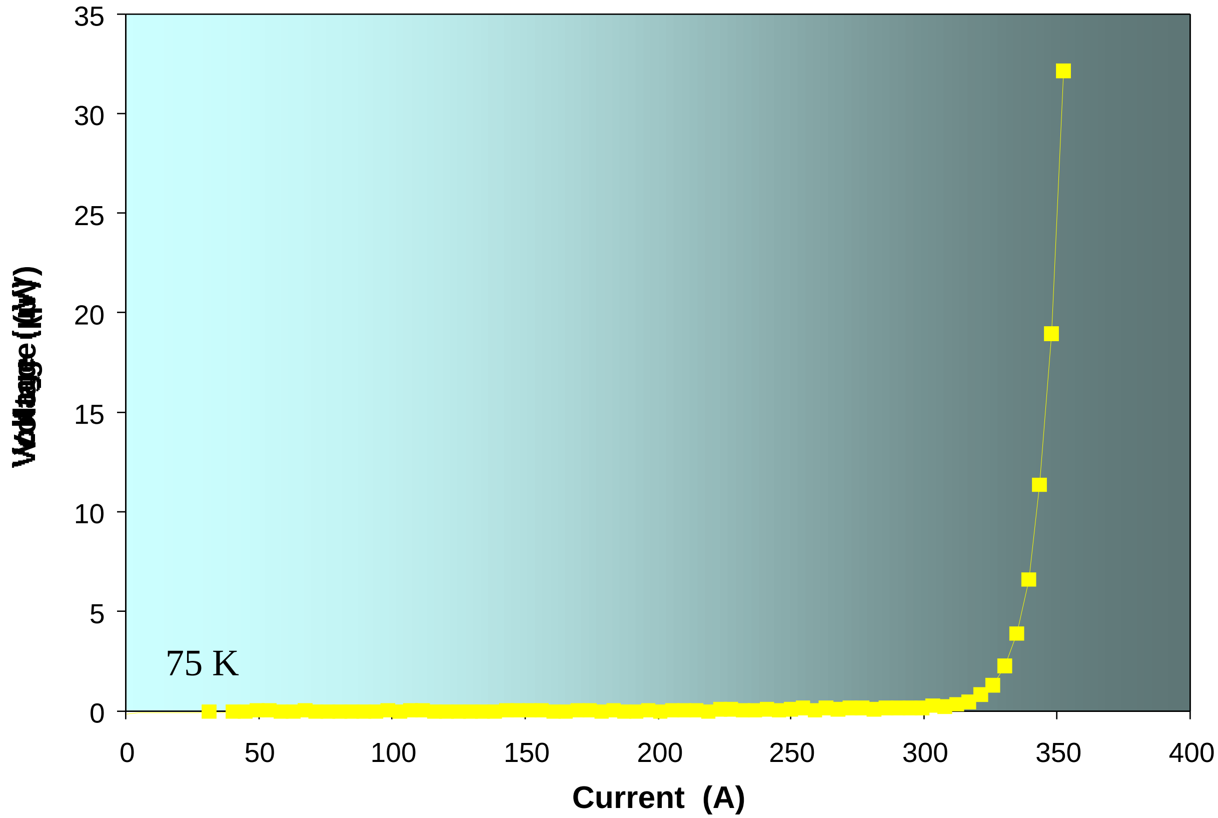
I_c along the length of a cm-wide tape measured at 75 K, 0.6 T (B||c)



We next measured the central 5 cm of the tape in field



The highest I_c measured as the external field approached zero was ~ 335 A



Finally, a cm-long piece of the tape was patterned into bridges to yield more information

- Superconductor thickness: 1.9 µm
- Estimated thickness of each YBCO layer: 0.9 µm
- T_c (inductive): 92.8 K
- J_c of the bridges (~200 µm x 5 mm): 2.05 & 2.15 MA/cm^2
- Extrapolated I_c: 400 A/cm-width

Conclusions

- We have found that Y/Sm-123 multilayers can be improved by reducing the Sm layer thickness and by increasing the number of layers.
- Using a conservative multilayer design (only 3 layers), we have produced a short, continuously processed tape with $I_c > 335$ A.
- The same multilayer design was extended to two one-meter lengths with resulting I_cs of 142 A and 189 A.
- The multilayer approach is a viable method for greatly increasing coated conductor performance.

FY 2001 Results

- Improved the continuous processing of IBAD MgO and -- without RHEED monitoring -- produced several meter-long tapes with average in-plane alignment of better than 9 degrees.

- Used a continuously processed IBAD MgO tape to fine-tune deposition parameters for buffer and YBCO layers. Result: 24 samples with an average J_c of 0.89 MA/cm^2 and an average equivalent I_c of 125 A/cm-width at 75 K.

- Coated two 4 cm long x 1 cm wide IBAD MgO strips: 73 A and 93 A.

- Best IBAD MgO full meter result: I_c = 14 A (75 K).

FY 2001 Results (continued)

- Obtained six one meter lengths of high-quality IBAD YSZ from the Center for Applied Materials Development, Göettingen, for research on superconducting multilayers. Using this material:

- Found that the highest I_c in YBCO/Sm-123 multilayers was obtained with thinner Sm-123 interlayers and/or thinner YBCO layers;

- Produced two one-meter tapes with multilayer coatings having I_c (75 K) values of 134 and 189 A;

FY 2001 Results (continued)

- Coated a 20 cm tape segment with a multilayer having an I_c (75 K, 9 cm measurement length) of over 335 A.
- Assisted in the design, layout, equipment specification, and staffing of the Los Alamos Research Park.

FY 2001 plans
(presented last year)

⇨ Produce a meter length of coated conductor using IBAD MgO having an end-to-end I_c of > 50 A.

⇨ Scale up a high-current modified coating process to produce first short lengths and then meter lengths of tape with I_c > 200 A/cm-width.

⇨ Deposit high I_c coatings on thinner substrates with a goal of reaching a J_e of 100 kA/cm^2.

⇨ Begin staffing and equipment procurement for the IBAD/PLD scale-up facility in the Industrial Research Park.

⇨ Continue the collaboration with Oak Ridge National Laboratory with a goal of coating meter lengths of their textured/seeded nickel using our continuous PLD process.

FY 2001 Performance

- ⇨ *Produce a meter length of coated conductor using IBAD MgO having an end-to-end I_c of > 50 A.*

  Using continuously coated IBAD MgO, produced 24 bridge samples with an average equivalent I_c of 125 A, and two 4 cm long x 1 cm wide strips with measured I_cs of 73 and 93 A. Our best meter length at 75 K is 14 A end-to-end.

- ⇨ *Scale up a high current modified coating process to produce first short lengths and then meter lengths of tape with I_c > 200 A/cm-width.*

  We coated a cm-wide segment of IBAD YSZ tape from Germany with a YBCO/Sm-123 multilayer that had an I_c of > 335 A through a 9 cm measurement length. A meter-long tape, processed in the same way, reached an I_c value of 189 A end-to-end (75 K).

FY 2001 Performance (continued)

⇨ *Deposit high I_c coatings on thinner substrates with a goal of reaching a J_e of 100 kA/cm^2.*

The total thickness of the cm-wide, 335 A tape was 53 microns: J_e = 63,000 A/cm^2. Bridges from a different part of the same tape had an equivalent I_c of 401 A: J_e = 75,000 A/cm^2.

⇨ *Begin staffing and equipment procurement for the IBAD/PLD scale-up facility in the Industrial Research Park.*

As presented to the Systems Panel yesterday, we have hired four new permanent staff for the Research Park, and have approximately half of the necessary equipment in house or on order.

FY 2001 Performance (continued)

⇨ *Continue the collaboration with Oak Ridge National Laboratory with a goal of coating meter lengths of their textured/seeded nickel using our continuous PLD process.*

Oak Ridge has supplied us with a meter length of high-quality buffered RABiTS tape, plus some shorter segments for test purposes. Our first test with a 4 cm long x 1 cm wide strip yielded a lower-than-expected I_c, indicating a need for further development work at Los Alamos before coating the meter.

FY 2002 Plans

- Continue improving the YBCO performance on meter lengths of IBAD MgO with a goal of bringing it up to par with YBCO on IBAD YSZ.
- Work toward reducing the number of layers in the IBAD MgO process.
- Develop a better scientific understanding of how thick multilayers improve tape current.
- Provide assistance in transferring our best IBAD and PLD technologies to the Los Alamos Research Park.
- Continue the collaboration with Oak Ridge National Laboratory with a goal of coating meter lengths of their textured/seeded nickel using our continuous PLD process.